CALIFORNIA ENERGY COMMISSION

Final Report Compilation for

Whole Building Diagnostician Demonstration

TECHNICAL REPORT

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The Program's final report and its attachments are intended to provide a complete record of the objectives, methods, findings and accomplishments of the Energy Efficient and Affordable Commercial and Residential Buildings Program. This attachment is a compilation of reports from Project 2.4, *Whole Building Diagnostician Demonstration*, providing supplemental information to the final report (Commission publication #P500-03-096). The reports, and particularly the attachments, are highly applicable to architects, designers, contractors, building owners and operators, manufacturers, researchers, and the energy efficiency community.

This document is one of 17 technical attachments to the final report, consolidating three research reports from Project 2.4:

- *Final Report – Single Building Operator Demonstration – On-line Testing (Mar2003)*
- *Final Report – Multi-Building Operator Demonstration – On-line Testing (Aug 2003)*
- *Final Report – Mechanical Services Provider Demonstration – On-line Testing (Jul 2003)*

The Buildings Program Area within the Public Interest Energy Research (PIER) Program produced this document as part of a multi-project programmatic contract (#400-99-011). The Buildings Program includes new and existing buildings in both the residential and the nonresidential sectors. The program seeks to decrease building energy use through research that will develop or improve energy-efficient technologies, strategies, tools, and building performance evaluation methods.

For the final report, other attachments or reports produced within this contract, or to obtain more information on the PIER Program, please visit www.energy.ca.gov/pier/buildings or contact the Commission's Publications Unit at 916-654-5200. The reports and attachments, as well as the individual research reports, are also available at www.archenergy.com.

Abstract

Project 2.4, *Whole Building Diagnostician Demonstration*.

Air handlers in commercial buildings often do not function properly due to sensor faults, control problems or scheduling errors. The objective of this project was to evaluate the usability of the Outdoor Air Economizer (OAE) module of the Whole Building Diagnostician (WBD) software, and to field test the software under three types maintenance management arrangements. Battelle, which developed the WBD under contract with US DOE, trained and supported use of the OAE by the operations staff of a large commercial office building, the energy manager of a government building campus, and the controls manager for a mechanical contractor providing services to a large commercial office building owner.

- The OAE was successful in detecting sensor and hardware problems as well as control setting problems at all of the demonstration sites.
- Fully automated data collection from some building automation systems was a challenge for the WBD. This can be overcome by working with BAS vendors and will, over time, likely disappear as better communications standards come into use.
- Once problems were identified by the OAE, too often no action was taken to make repairs. This suggests that a mechanism is needed for delivering the results to users in a way that better encourages them to correct the problems found, which may require changing incentives and rewards to inspire action by building staff.

This document is a compilation of three technical reports from the research.

PNWD-3255

Task Report for the

Energy Efficient and Affordable Small Commercial and Residential Buildings Research Program

a Public Interest Energy Research Program sponsored by the California Energy Commission

Project 2.4 – Demonstration of the Whole-Building Diagnostician

Task 2.4.5a – Single-Building Operator Demonstration – On-line Test

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1 Executive Summary

This report on Task 2.4.1 – On-line Test for the Single-Building Operator Demonstration for Project 2.4 – Demonstration of the Whole-Building Diagnostician documents the results of the single-building-operator, on-line, demonstration conducted at the Symphony Towers building in San Diego, California.

The on-line test was designed to evaluate the Outdoor-Air Economizer (OAE) diagnostic module's capabilities to automatically and continually diagnose operational problems with air-handling units (AHUs). As part of this demonstration, all four AHUs at Symphony Towers were monitored. The measured data that were collected on a continuous basis included: 1) outdoor-air temperature, 2) return-air temperature, 3) mixed-air temperature, 4) supply-air temperature, 5) chilled-water valve position, 6) supply-fan status, 7) outdoor-air relative humidity, and 8) return-air relative humidity. The relative humidities of the air streams were needed because the AHUs at Symphony Towers used enthalpy-based economizer control. Because the building was heated using hot water that was supplied directly to the terminal units, hot-water valve position was not monitored at this site.

The air-handler control strategy for outdoor-air ventilation and economizing, and the schedule (times of day and days of week) for which the minimum outdoor air must be supplied for the occupants were entered into the WBD's configuration for each air handler. This information was largely obtained from Symphony Towers' staff; some items were ascertained by observation of the raw data delivered, as is typical in most WBD installations. Symphony Towers was found to not have a fixed schedule for outdoor-air supply.

For on-line tests, data from the AHUs were automatically collected and logged into the diagnostician's database using a data acquisition module, which is part of the Whole Building Diagnostician. Although data requests can be made at any frequency, at Symphony Towers, the data were requested at 5-minute intervals and integrated over the hour before being processed by the OAE diagnostic module. The on-line data collection process started in April of 2000 for all four AHUs. The data collection process worked well when all parts of the software were properly running. There were several occasions where the data acquisition module on the operator's workstation was manually terminated and this went undetected for several weeks. Although several weeks of data were lost as a result of this problem, all four AHUs have more than a year of data.

All four AHUs at Symphony Towers had unresolved problems. The predominant problem for each of the four AHUs are: 1) AHU-1 had the minimum damper position set too high, 2) AHU-2 had a temperature sensor problem (most likely the mixed-air temperature sensor), 3) AHU-3 had a temperature sensor problem (either outdoor- or mixed-air sensor) and 4) AHU-4 also had a temperature sensor problem (the outdoor-air sensor).

When an AHU has a faulty temperature sensor, cost impacts cannot be calculated directly. More detailed analysis using estimation procedures is required to estimate the energy impacts from faulty temperature sensors. As a result, energy impacts were not estimated for the three AHUs with faulty temperature sensors. Energy impacts for AHU-1 were estimated using a simplified method implemented in a spreadsheet, which is described in the report. The annual cooling energy impact for this problem for typical San Diego weather is about 81,000 kWh, and the corresponding annual cost impact is about $12,000.

Although the problems identified by the OAE diagnostician were known to the building operators, only one problem (which was found during the off-line test and corrected immediately after it) was corrected during the demonstration.

Mr. Dishman, energy manager for Symphony Towers, indicated that the WBD tool set was useful and added that he would like more diagnostic tools such as WBD for other heating ventilation and air-conditioning (HVAC) systems. Mr. Dishman indicated that the user interface for both the WBD and the OAE diagnostician were easy to use. Although the problems identified by the OAE diagnostician were know to the building manager and operators, only one problem was corrected (immediately after the off-line test). In addition, the building operators were trained on how to view OAE results and interpret the information it provides; none of them actually reviewed the results during the demonstration. This may be a critical missing link in the process of using such tools that needs further investigation in future applications.

The OAE diagnostician successfully identified problems with all four AHUs at Symphony Towers. These findings are consistent with the other field demonstrations of the WBD where the OAE found similar problems that should have been detected during commissioning. The demonstration showed that diagnostic technology can provide useful information on equipment status but its value isn't realized unless building staff implement fixes to the problems. It is insufficient to merely identify problems and their impacts; building staff must correct them. If users are not proficient in using their control systems to correct problems, are too busy with other duties, or lack resources to obtain help from contractors, diagnostic technologies alone will not provide system-efficiency improvements. The staff at Symphony Towers were occupied with renovation and upgrading activities during this demonstration and did not find time to correct the problems detected by the OAE. If timing had been different, staff might have corrected these problems. In general, however, improvements can only be realized in buildings where identified problems are corrected. Future demonstrations or broad deployment of the WBD must include a mechanism for ensuring that identified problems get fixed. This could be done by building staff or outside service providers, but it is necessary if diagnostics are to do more than simply identify problems and actually proceed to deliver energy savings.

2 Purpose of This Task Report

In April 2000, the California Energy Commission (CEC) initiated a project to evaluate a DOE-developed technology, the Whole-Building Diagnostician (WBD), for automatically and continually diagnosing operational problems in buildings. The Whole-Building Diagnostician is a pre-commercial, production-prototype software package that connects to digital control systems (e.g., energy management systems), utilizing data from the control system's sensors to analyze overall building and system performance. It currently consists of two diagnostic tools, or modules, with a user interface designed to readily identify problems and provide potential solutions to building operators. The Outdoor-Air Economizer module (OAE), the subject of this demonstration, diagnoses whether each air handler in a building is supplying adequate outdoor air for the occupants it is designed to serve, by time of day and day of week. It also determines whether the economizer is providing free cooling with outside air when appropriate and not wasting energy by supplying excess outside air. In addition to the two diagnostic modules, the WBD also has a data module to automatically retrieve data from some building automation systems.

This report documents the results of **Task 2.4.1 – On-line Test for the Single-Building Operator Demonstration for Project 2.4 – Demonstration of the Whole-Building Diagnostician.** The single-building operator demonstration was conducted at the Symphony Towers building in San Diego. Some characteristics of the building are listed in the next section.

This project is intended to demonstrate the WBD's current automated diagnostic tools in three contexts:

- **Single-Building Operator Demonstration –** use of the WBD by dedicated operators for a single, Class A office building

- **Multi-Building Operator Demonstration –** use of the WBD by a set of supervisory operators for a set of commonly managed and operated buildings that share a control system infrastructure

- **Service Provider Demonstration –** use of the WBD by third-party analysts of a service company providing contracted retrofit and operations and maintenance (O&M) services to buildings and facilities.

In each of these three contexts, Project 2.4 is designed to test and demonstrate automated diagnostics using the Whole-Building Diagnostician in actual buildings with actual operators and energy service providers to:

- prove their efficacy in automatically detecting energy efficiency and outdoor-air supply problems in buildings

- test and demonstrate the ability of users to interpret and act upon the information provided by the tools to correct building operational problems

- develop case studies of the impacts of using the tools in terms of the type and number of problems found, the energy savings and fresh air supply impacts of correcting the problems

- provide early feedback from users, based on their experiences with actual automated diagnostic tools, to guide development and implementation of other tools in the future, including those in the program plan.

This report focuses on the on-line test results for the single-building operator demonstration and is a follow up to an earlier report that described the off-line test results for the same site. After the demonstration site was selected, the demonstrations began with an off-line test of the WBD's Outdoor-Air Economizer diagnostic module. The off-line test was designed to determine the basic suitability of the demonstration site for testing the WBD. The three major criteria to determine the suitability were: accessibility of the control system sensors for data collection, whether the necessary sensors were present and reasonably accurate, and whether the control strategy for the air handlers' outdoor-air economizer systems could be diagnosed by the OAE module. Off-line testing of the OAE module at Symphony Towers was successful because all three major criteria were satisfied.

The results of the on-line demonstration are presented in this report. In the section following this, the need for diagnostics in building systems is briefly discussed, followed by a section on basic information about what the Whole-Building Diagnostician is, how it works, and a detailed description and capabilities of the OAE module. The Symphony Towers building is described next. Technical discussions including installation of the WBD, training of the Symphony Towers staff, the WBD's operation, problems identified by the OAE, potential savings from correcting the problems found, and issues surfaced that have implications for facilities that might wish to use the WBD are also presented.

3 Symphony Towers Building

The single-building operator demonstration took place at the Symphony Towers building in San Diego, California. Crowned the "International Building of the Year" by the Building Owners and Managers Association, (BOMA) in 1994, Symphony Towers is a 34-story 601,000 sq. ft., "Class-A", mixed-use development located at the hub of downtown San Diego's financial corridor. Its net rentable floor space is 528,869 ft^2, mostly leased to tenants who are legal and accounting firms. There is a private dining facility on the top floor.

Symphony Towers was selected for the demonstration because of its visibility and energy conscious management. In San Diego, Symphony Towers is a superior property, affiliated with numerous associations including the BOMA, The International Facility Managers Association (IFMA), The Association of Energy Engineers (AEE), and the San Diego Building Engineers Association (SDBEA).

The building owner is SPP Investment Management, which has a growing portfolio of 37 buildings in the U.S. In the U.S. Region, Symphony Towers is the "King Pin" project for the owner. Building operation has recently been contracted to StepStone Real Estate Services, but the core of the engineering team remains intact. The team has aggressively pursued optimal equipment performance and has accomplished numerous lighting, mechanical, plumbing, and controls enhancements.

The building's HVAC (heating, ventilating and air-conditioning) system consists of two three-stage centrifugal chillers of 550 tons each, and two natural gas hydronic boilers of 3,000 MBtu/hr each. The occupied space is served by four variable-air-volume air handlers, equipped with enthalpy-controlled economizers and variable speed drives (see Table 1). The air handlers only supply cooling; no heating coil is present. The control system is manufactured by Johnson Controls Metasys, and provides convenient on-demand access to data by the WBD via a DDE (dynamic data exchange) server.

Table 1. Symphony Towers Air Handlers in the Demonstration

Air-Handler	Rated Flow (ft^3/min)
AHU-1	80,000
AHU-2	144,000
AHU-3	144,000
AHU-4	126,000

At the start of the demonstration (March 2000), the primary contact at Symphony Towers was Jim Ford, Chief Engineer and Energy Manager. Jim Ford left Symphony Towers and was replaced by Richard Dishman in 2000. Initially Jim Ford and later Richard Dishman was the primary administrator of the WBD at Symphony Towers (The Administrator has the highest-level permissions to change the configuration of the WBD to reflect changes to controls, add diagnosticians, rename buildings and components, reprocess data, etc.)

Symphony Towers is the second test of the WBD at a private-sector building; the first was done at a large hotel in San Francisco. This demonstration is a continuation of an earlier demonstration funded by the U.S. Department of Energy as part of the WBD development effort. The earlier demonstration began in December of 1999 and continued through Fiscal Year[1] (FY) 2000, when it became part of this project. During that time significant improvements were made to the WBD, and these were tested in this demonstration.

[1] The federal fiscal year runs for October 1 through September 30. For example, FY2000 ran from October 1, 1999, through September 30, 2000.

4 The Need for Diagnostics in Building Systems

Automated commissioning and diagnostic technologies are designed to ensure the ongoing performance of buildings at the highest possible levels of efficiency. Evidence of extensive performance problems in buildings shows that an efficient building stock will not result from solely designing efficient buildings and installing efficient equipment in them (Lunneberg 1999; also check the commissioning resources at http://www.peci.org).

These performance problems are not inherent with efficiency technologies themselves, but instead result from errors in installation and operation of complex building heating/cooling systems and their controls. It is also significant that these systems are becoming increasingly more sophisticated to obtain ever higher levels of energy efficiency, adding to the complexity and subtlety of problems that reduce the net efficiency acquired. Such problems are even more common in existing buildings because they arise over time from operational changes and lack of maintenance (Claridge et al. 2000; also check the commissioning resources at http://www.peci.org). They often result in problems with comfort control and indoor-air quality, which affect occupant health and productivity (Daisey and Angell 1998).

Assuring efficient performance by commissioning of new buildings followed by regularly-scheduled preventative maintenance is clearly insufficient to address this issue. Manually commissioning[2] buildings is valuable in terms of both finding problems and developing the techniques for doing so, but, it is expensive. With only 1 to 2% of total construction costs devoted to commissioning (see the commissioning resources at http://www.peci.org) and the few experts available to provide such services in high demand, commissioning is not done adequately for most commercial buildings. Commissioning is difficult to sell in a low-bid construction environment, where variations in the effort allocated to commissioning can be the difference between winning and losing bids and where building owners (rightfully) feel they should not have to pay extra to get buildings to work properly. Further, commissioning is often short-changed because it largely occurs at the end of the construction process, when time-to-occupancy is critical and cost overruns drive last minute budget cuts in remaining items.

Effective, on-going maintenance of building systems as usually performed is notably ineffective, being almost exclusively complaint-driven and “quick fix” oriented. This is especially true for problems affecting air quality and efficiency because they are “silent killers” that go unnoticed until complete system failure occurs.

By embedding the expertise required to detect and diagnose operation problems in software tools that leverage existing sensors and control systems, detection and diagnosis can be conducted automatically and comprehensively without the ongoing cost of expensive human expertise. Further, this oversight remains as a legacy in buildings after they are constructed, protecting the building systems against slow mechanical degradation, as well as faults inadvertently introduced

[2] Commissioning is the process of systematically putting a building “through its paces,” checking that it performs as expected in terms of sensor and actuator connectivity and calibration, system modes, control sequences, and equipment capacities and conversion efficiencies. The term derives from the traditional acceptance process for naval ships, which must undergo a shakedown cruise to prove their speed, range, stability, maneuverability, communications, etc., to meet design specifications before they are accepted into service.

by operators seeking to resolve complaints without finding root causes. The principal technical challenges are the construction of diagnostic techniques that 1) can be automated, 2) comprehensively diagnose the range and diversity of building systems and equipment, 3) make use of a minimal set of additional sensors beyond those used for control, and 4) are applicable for building commissioning, as well as on-going diagnostics.

Currently, most building owners are not aware of the power of automated commissioning and diagnostic technology to provide them more cost effective, comfortable, and productive buildings. The technology is in its infancy and not yet well know in practice. Finally, energy service companies who may eventually offer commissioning and diagnostic services are slow to expand their business practices beyond their current focus on lighting and cooling equipment retrofits. Despite this current state, automated diagnostic technology offers promise of a future with improved facility operation, better indoor environments, and enhanced and higher-quality offerings by service companies.

5 Background on the WBD

Developed by the Pacific Northwest National Laboratory (PNNL)[3] under funding from the Office of Energy Efficiency and Renewable Energy of the U.S. Department of Energy, with Honeywell, Inc. and the University of Colorado as subcontractors, the Whole-Building Diagnostician is a production-prototype software package with two modules providing automated diagnostics for buildings based on data collected by direct-digital control (DDC) systems. These tools are deployed in the WBD's user interface and data and process management infrastructure.

The WBD's Outdoor-Air Economizer module diagnoses whether each air handler in a building is supplying adequate outdoor air for the occupants it is designed to serve, by time of day and day of week. It also determines whether the economizer is providing free cooling with outdoor air when appropriate, and is not wasting energy by supplying excess outdoor air. Few, if any, sensors other than those used to control most economizers are required, making the OAE practical in near-term markets because of its low cost. Early experience with the OAE in new and existing buildings in Washington and California has confirmed the broadly held suspicion that problems with outdoor-air ventilation control and economizing are endemic. The OAE has discovered problems in all but 1 of the roughly 35 air handlers examined to date, in existing and newly commissioned buildings.

The WBD also contains a Whole-Building Efficiency module that monitors whole-building and major subsystem (end-use) performance. It does this by tracking actual energy consumption and comparing it to estimated expected consumption as a function of time of day, day of week, and weather conditions. Using these data, it automatically constructs a model based on actual past system performance for a baseline period, and then alerts the user when performance is no longer as good as or, in the case of retrofits or operations and maintenance programs, is better than past performance. The tool bootstraps itself to provide feedback during the initial training period after a period of about 4 to 6 weeks. Electricity or gas consumption sensors typically must be connected to the building's direct digital control system to obtain the consumption data. This, however, is not an absolute requirement.

Both modules provide information to users in simple, graphical displays that indicate the presence or absence of problems at a glance. They also provide cost estimates of detected energy waste to provide feedback to users on the relative importance of the problems detected. These tools are available for commercialization through special use licenses from Battelle. The WBD's infrastructure is an open-protocol, public-domain framework designed to support the ready incorporation of new diagnostic tools from other developers in the future.

5.1 The WBD Infrastructure

The WBD currently consists of four primary modules: the two diagnostic modules, the user interface, and a database that stores measured data, as well as diagnostic results. These are connected by an infrastructure that provides data transfer, data management, and process control, as shown in Figure 1. Boxes represent major components; lines represent flows of data. Data is automatically obtained at a user-specified sub-hourly frequency and averaged to create hourly values. As new hourly values become available in the database, the diagnostic modules

[3] Operated for the U.S. Department of Energy by Battelle Memorial Institute under Contract DE-AC06-76RL01830.

automatically process them and produce diagnostic results that are also placed in the database. The user can then open the WBD user interface at any time to see the latest diagnostic results, and can also browse historical results.

Raw data (e.g., sensor measurements) may be obtained from a variety of data sources: a data logger or building management system, another database, or some other analytic software tool. The system also requires one-time entry of setup data that customizes the WBD modules to each specific building and heating/cooling/ventilation system. The system is written in the C++ language and uses an SQL database. The term DDE in Figure 1 refers to Microsoft's Dynamic Data Exchange protocol.

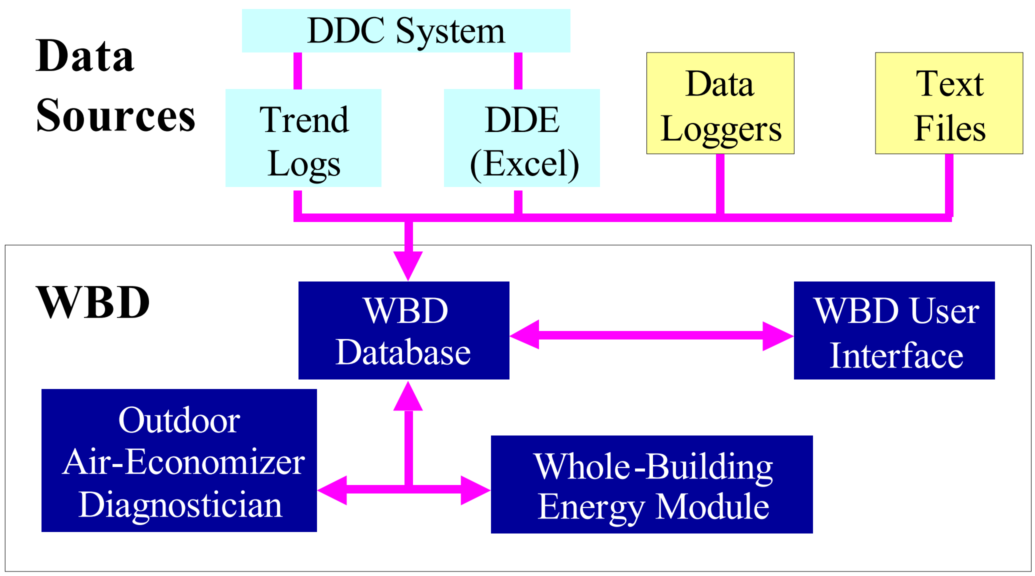


Figure 1 – Schematic Diagram of the WBD Software

6 The Outside-Air Economizer (OAE) Diagnostic Module

This section provides a brief overview of the Outside-Air Economizer (OAE) module. Additional information about the WBD and the OAE can be found in Brambley et al. (1998) and Katipamula et al. (1999). The OAE continuously monitors the performance of air handlers and can detect basic operation problems or faults with outside-air control and economizer operation. The current version detects about 25 different basic operational problems and over 100 variations of them [for details refer to Brambley et al. (1998) or Katipamula et al. (1999)]. It uses color coding to alert the building operator when problems occur and then provides assistance in identifying the causes of problems and advice for correcting them. It, however, does not detect problems with the water-side or the refrigerant side of the air handler; it only detects problems on the air side, i.e., economizer operation and ventilation. If the air handler does not have an economizer, the OAE module can still detect problems with the outdoor-air ventilation.

6.1 Types of Economizer Controls Supported

The OAE module can diagnose abnormal operations or problems with several different types of economizer controls including: differential dry-bulb temperature-based, differential enthalpy-based, high-limit dry-bulb temperature-based and high-limit enthalpy-based.

With differential control strategies, the outside-air condition is compared with the return-air condition. As long as the outside-air condition is more favorable (for example, with dry-bulb temperature control, the outside-air dry-bulb temperature is less than the return-air temperature), outside air is used to meet all or part of the cooling demand. If the outside air alone cannot satisfy the cooling demand, mechanical cooling is used to provide the remainder of the cooling load.

With high-limit control strategies, the outside-air condition is compared to a single or fixed set point (usually referred to as a high limit). If the outside-air condition is below the set point, outside air is used to meet all or part of the cooling demand. Any remaining cooling load is provided by mechanical cooling.

In addition to these economizer control strategies, the OAE supports fault detection with both integrated and nonintegrated economizers. An integrated economizer, as its name implies, is fully integrated with the mechanical cooling system such that it can either provide all of the building's cooling requirements if outdoor conditions allow, or it can supplement mechanical cooling when outdoor conditions are not sufficiently favorable to handle the entire cooling load. An economizer often has the ability to throttle outdoor-air intake rates between minimum and maximum levels to prevent the delivered air from being cooler than the supply-air set point.

Conversely a nonintegrated economizer does not operate when the mechanical cooling system is operating. If outdoor conditions are not sufficiently favorable to allow 100% economizing, no economizing is used. A two-stage thermostat often controls a nonintegrated economizer. The first stage opens the economizer; the second stage locks out the economizer and turns on the mechanical cooling.

6.2 Types of Air-Handling Systems Supported

The OAE tool supports the following types of single-duct air handlers:

- Constant-air-volume systems
- Variable-air-volume (VAV) systems with no volume compensation (i.e., outside-air intake is a constant fraction of the supply-air flow rate rather than changing it to maintain a constant outside-air volume).

Air handlers that the OAE tool does not support include:

- VAV systems that maintain constant outside-air volume flow through volumetric flow measurements (commonly using air-monitoring stations consisting of pitot-tube arrays)
- VAV systems that attempt to approximately provide constant outside-air volumetric flow by increasing the outside-air fraction (e.g., by opening the outside-air damper system) as the fan speed decreases
- Systems that utilize CO_2-based outside-air control strategies
- Dual-duct air-handling systems.

6.3 Metered Data Requirements for the OAE Module

The OAE requires seven periodically measured/collected (currently at sub-hourly increments) variables, as shown in Figure 2 (bold labels in the figure identify required data). In addition to the seven variables, the damper-position signal is also required for air handlers with damper-position-signal control, i.e., if the damper-position signal is controlled directly to maintain the ventilation or to control the supply- or mixed-air temperatures when the air handler is economizing. For economizers with enthalpy-based control, outside- and return-air relative humidities (only for differential enthalpy control) or dew-point temperatures are required. If the supply- or mixed-air temperature set point is reset, the reset value at each hour is also needed.

6.4 Setup Data Requirements

The OAE module requires several one-time (setup or configuration) data inputs to characterize the existing systems and define how they are controlled. In addition to the setup data, the OAE also requires at least seven metered data points (same as variables called out in Figure 2). The engineering units for all inputs (both setup and measured) are assumed to be in Inch-Pound units unless otherwise specified.

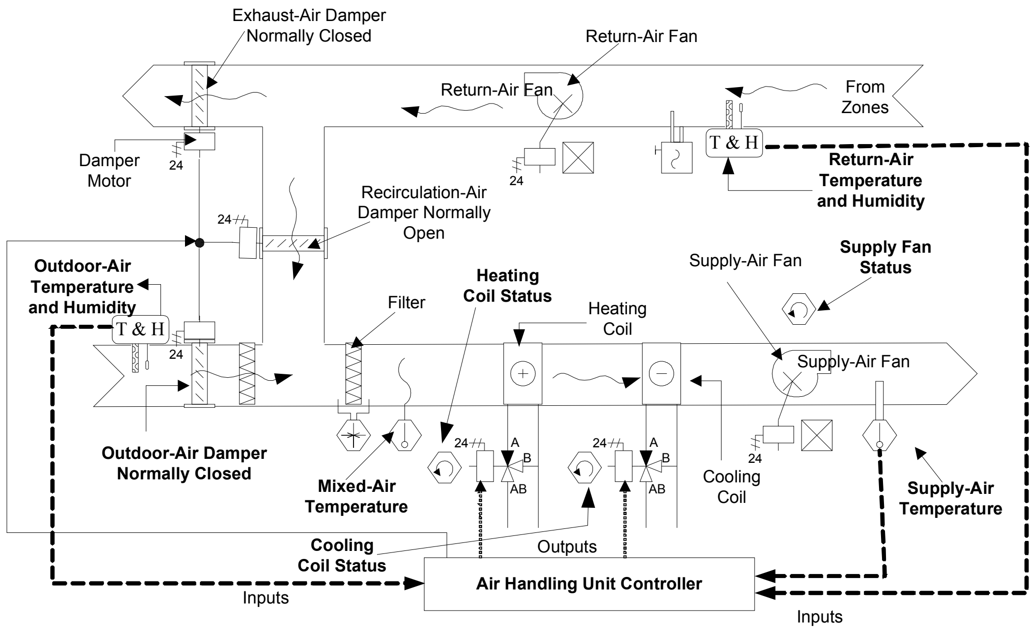


Figure 2 – Schematic Diagram of an Air Handler Showing the Sensor Locations

The OAE is capable of detecting and diagnosing faults with most commonly found air handlers using almost all outside-air and economizer control strategies. However, the user must describe the control strategies used to the OAE with the setup information. In addition, the OAE is designed to be flexible in accepting status inputs. For example, the WBD can accept any one of four different types of signals to indicate whether the supply fan is ON. Once the OAE module is configured, the detection and diagnosis is fully automated.

The setup data are required for all air-handler systems with economizers. These data describe:

1. the basic air-handling system
2. the minimum, maximum, and required (building fully-occupied) outdoor-air fractions
3. the occupancy schedule, defining when the required outdoor air must be supplied
4. data needed to estimate energy and cost impacts of problems.

There are 17 items of setup data that must be supplied by the user for every air-handler system. In addition, there are a number of additional setup data inputs, along with the types of air handler and economizer controls to which they are applied. As few as 3 to as many as 15 additional inputs may be required to describe any given system type. For a typical system with an outdoor-air-fraction-based differential temperature economizer with low-limit control, nine of these setup items are required. Almost all of these inputs are provided with defaults that enable the OAE module to be initialized without the user providing them; however, it will not provide correct diagnoses unless the setup values are correct. Potential errors in the setup data are sometimes identified by the OAE as candidate causes of problems it detects with the air-handler operation. Generally, these then need to be reconciled by the building operator and setup data changed to correct any differences between the actual and default values.

6.5 Basic Operating Sequence of Air Handlers

The OAE module uses a logic tree to determine the operational "state" of outdoor-air ventilation and economizer systems at each point in time for which measured data are available. The logic tree is based on the basic air-handler operating sequence, as described below.

An air handler typically has two main controllers: 1) to control the outdoor-air intake and 2) to control the supply-air temperature (in some cases mixed-air temperature is controlled rather than supply-air temperature). The basic operation of the air handler is to draw in outdoor air and mix it with return air from the zones and, if necessary, condition it before supplying the air back to the zones, as shown in Figure 2.

An air handler typically has four primary modes of operation during a building's occupied periods, for maintaining ventilation (fresh-air intake) and comfort (the supply-air temperature at the set point), as shown in Figure 3. The operating sequence determines the mode of operation and is based on the ventilation requirements, the internal and external thermal loads, and indoor and outdoor conditions.

When indoor conditions call for heating, the heating-coil valve is modulated (i.e., controlled) to maintain the supply-air temperature at its set point (heating mode in Figure 3). When the air handler is in the heating mode, the cooling-coil valve is fully closed, and the outdoor-air damper is positioned to provide the minimum outdoor air required to satisfy the ventilation requirements. As heat gains increase in the zone and the need for cooling increases, the air handler transitions from heating to cooling. Before mechanical cooling is provided, the outdoor-air dampers are opened fully to use the favorable outdoor conditions to provide 100% cooling (economizer mode in Figure 3). In this mode, the heating- and the cooling-coil valves are fully closed and the outdoor-air dampers are modulated to meet all the cooling requirements.

As the heat gains in the zone continue to increase, the outdoor air alone cannot provide all the cooling necessary, and the air handler changes modes by initiating mechanical cooling (cooling and economizing mode in Figure 3) to supplement the economizer. In this mode, the outdoor damper is fully open, the heating-coil valve is fully closed, and the cooling-coil valve is modulated to maintain the supply-air temperature. As the outdoor conditions become unfavorable (i.e., too hot and humid) for economizing, the air handler changes mode again. This time the outdoor-air dampers are modulated to the minimum position to provide the minimum outdoor air required to satisfy the outdoor-air ventilation needs, the heating-coil valve continues to be fully closed, and the cooling-coil valve is modulated to maintain the supply-air temperature at its set point.

If an air handler does not have an economizer, there are two basic modes of operation (heating and mechanical cooling). If the economizer is not integrated with mechanical cooling (i.e., it cannot economize and provide mechanical cooling simultaneously), there are three basic modes of operation (heating, economizing, and mechanical cooling).

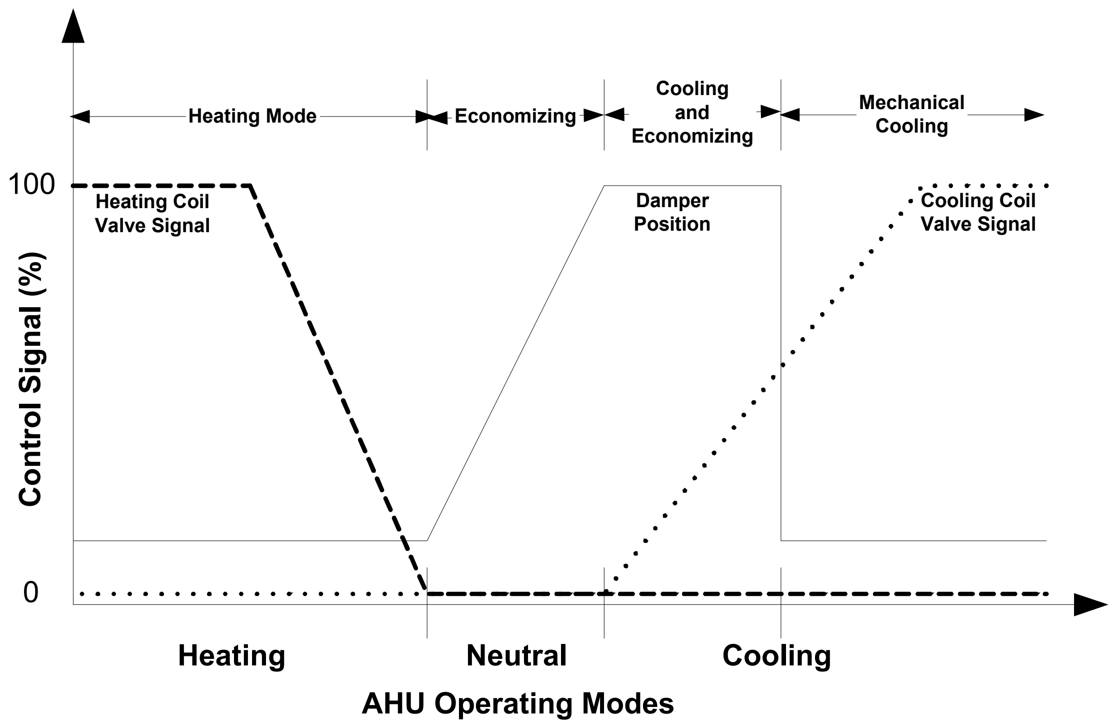


Figure 3 – Basic Operating Sequence of an Air-Handling Unit

6.6 Diagnostic Approach

The OAE uses rules derived from engineering models and understanding of proper and improper air-handler performance to diagnose operating conditions. The rules are implemented in a decision tree structure in the software. The OAE diagnostician uses periodically measured conditions (temperature or enthalpy) of the various air-flow streams, measured outdoor conditions, and status information (e.g., fan on/off status) to navigate the decision tree and reach conclusions regarding the operating state of the air handler. At each point in the tree, a rule is evaluated based on the data, and the result determines which branch the diagnosis follows. A conclusion is reached regarding the operational state of the air handler when the end of a branch is reached. Tolerances are assigned to each data point, and uncertainty is propagated through all calculations.

Many of the states correspond to normal operation and are dubbed "OK states." For example, one OK state is described as "ventilation and economizer OK; the economizer is correctly operating (fully open), and ventilation is more than adequate." For this case, the system is apparently operating correctly with the outdoor-air damper fully open to benefit to the maximum extent possible from cool outdoor-air used for free cooling. Ventilation rates for the occupants are also being met by the current outdoor-air ventilation rate. Other states correspond to something operationally wrong with the system and are referred to as "problem states." An example problem state might be described as "economizer should not be off; cooling energy is being wasted because the economizer is not operating; it should be fully open to utilize cool outside air; ventilation is adequate." As with the previous state, conditions are such that the outside-air damper should be fully open to benefit from free cooling; however, in this case the economizer is incorrectly off, yet the outdoor-air ventilation is still adequate to meet occupant needs. Thus, the building is experiencing an energy penalty from not using the economizer.

Other states (both OK and problem) may be tagged as incomplete diagnoses, if critical data are missing or results are too uncertain to reasonably reach a conclusion.

Each problem state known by the OAE module has an associated list of possible failures that could have caused the state; these are identified as possible causes. In the example above, a stuck outdoor-air damper, an economizer controller failure, or perhaps a misconfigured setup could cause the economizer to be off. Thus, at each metered time period, a list of possible causes is generated.

An overview of the logic tree used to identify operational states and to build the lists of possible failures is illustrated in Figure 4. The boxes represent major sub-processes necessary to determine the operating state of the air handler; diamonds represent tests (decisions), and ovals represent end states and contain brief descriptions of OK and problem states. Only selected end states are shown in this overview, and the details of processes and decisions are excluded because of space constraints.

6.7 Basic OAE Functionality

The OAE user interface uses color coding to alert the building operator when problems occur. It then provides assistance in identifying the causes of the problems detected and in correcting them. Figure 5, for example, shows a representative OAE diagnostician window. On the left pane of the window is a directory tree showing the various systems implemented in this particular WBD system. The tree can be used to navigate among the diagnostic results for various systems. In this case, results for air handler 12 (AHU-12) are highlighted in the tree. In the right pane is a color map, which shows the OAE diagnostic results for this air handler. Each cell in the map represents an hour. The color of the cell indicates the type of state. White cells identify OK states, for which no problems were detected. Other colors represent problem states. "Clicking" the computer mouse on any shaded cell brings up the specific detailed diagnostic results for that hour.

Figure 6 and Figure 7 show pop-up windows providing a short description of a problem, a more detailed explanation of the problem, energy impacts of the problem, potential causes, and suggested actions to correct each cause. The second window (Figure 7) labeled "Details" is revealed by "clicking" on the "Details" button in the first window (Figure 6). In this case, the problem investigated is a sensor problem. The current version of this OAE diagnostician cannot, by itself, isolate the specific sensor that has failed, but instead it suggests manual inspection and testing of the sensors and their wiring to identify the specific problem. Yet another example of OAE is shown in Figure 8, where a high energy consumption problem is evident.

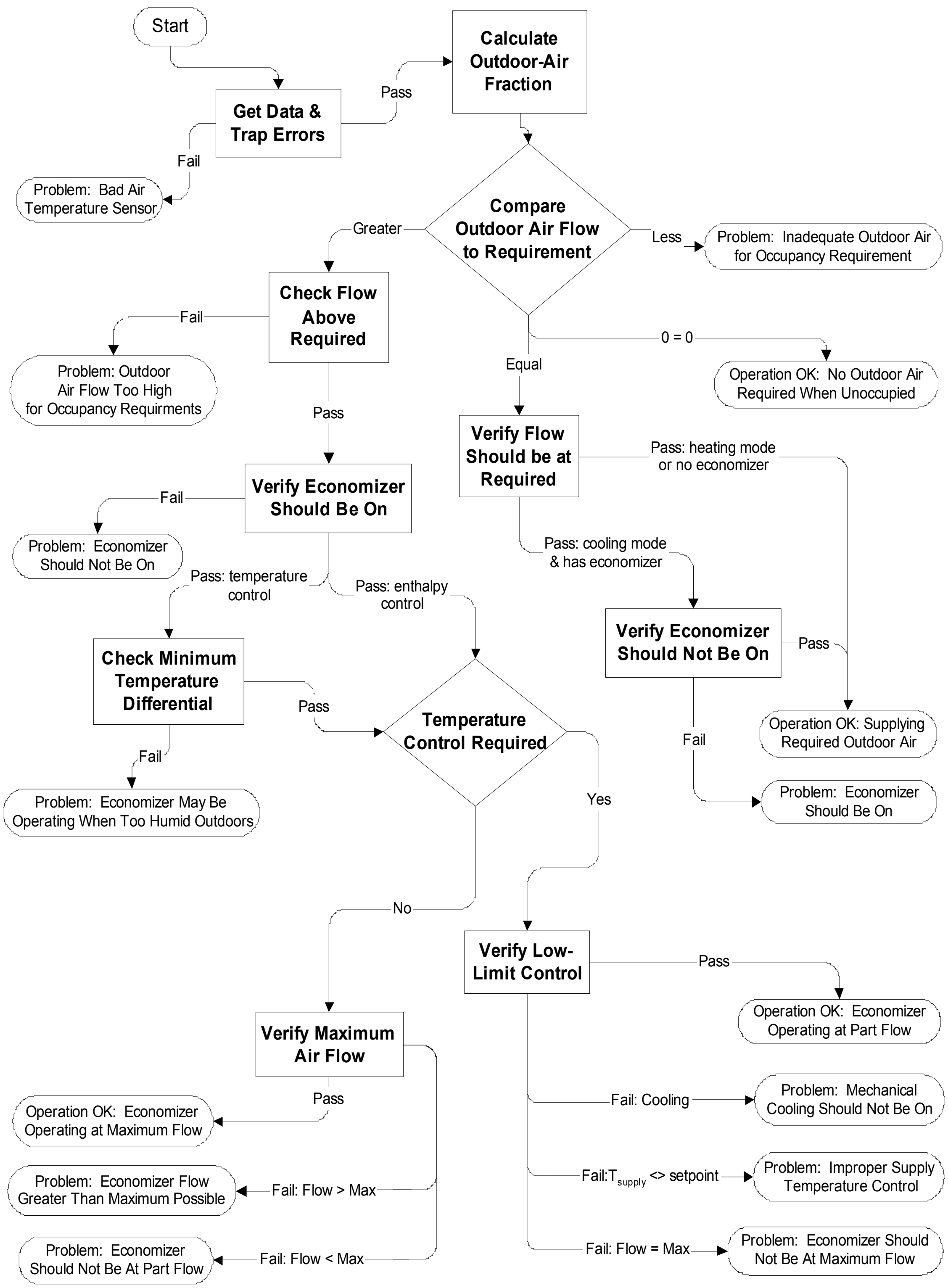


Figure 4 – Overview of the OAE Diagnostic Logic Tree Showing Key Decision Processes in Boxes and Operating States in Ovals

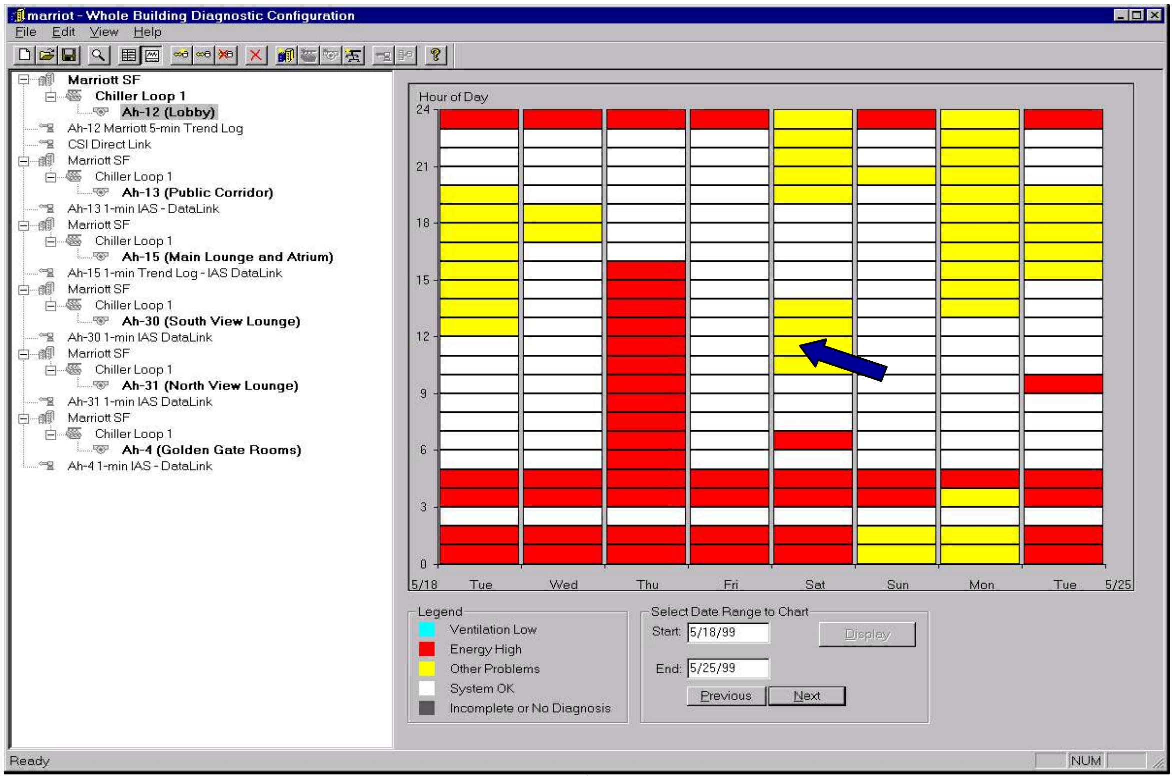


Figure 5 – Diagnostic Results Showing Proper and Faulty Operation for an Air Handler with a Faulty Outdoor-Air Temperature Sensor. The arrow identifies the cell for which more detailed results are given in Figure 6 and Figure 7

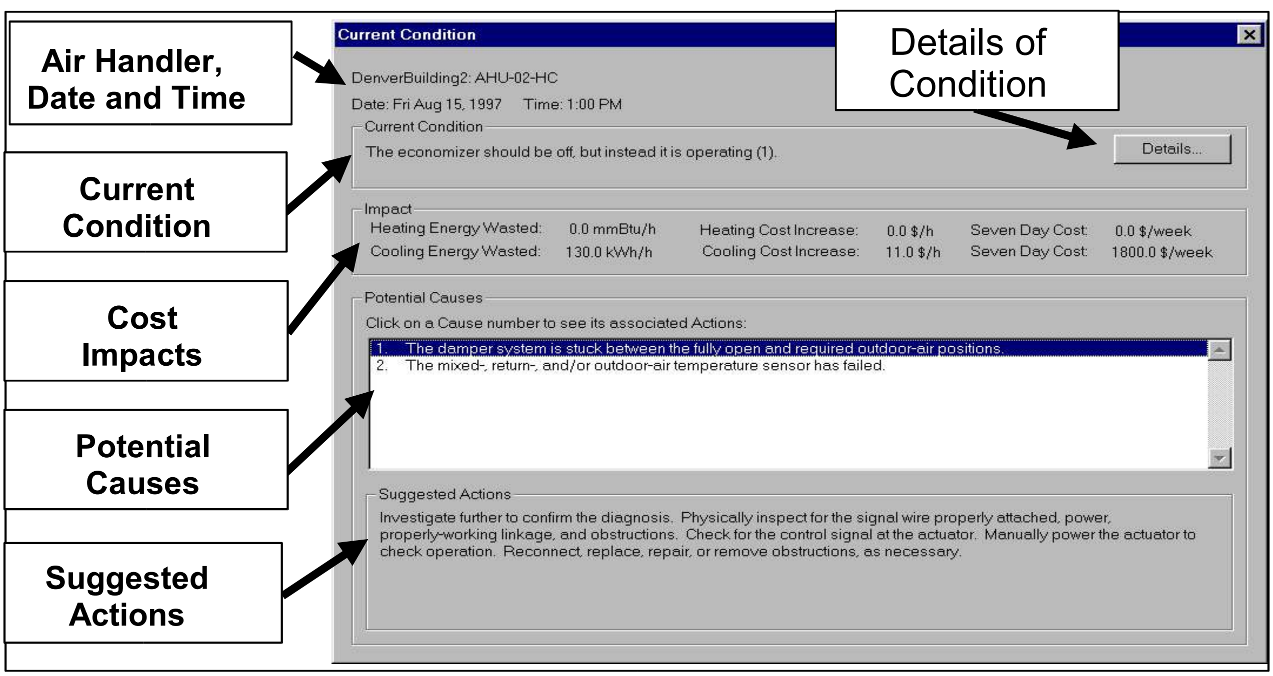


Figure 6 – Window Showing a Description of the Diagnosis, the Impacts of the Problem Found, Potential Causes of the Problem, and Suggested Corrective Actions.

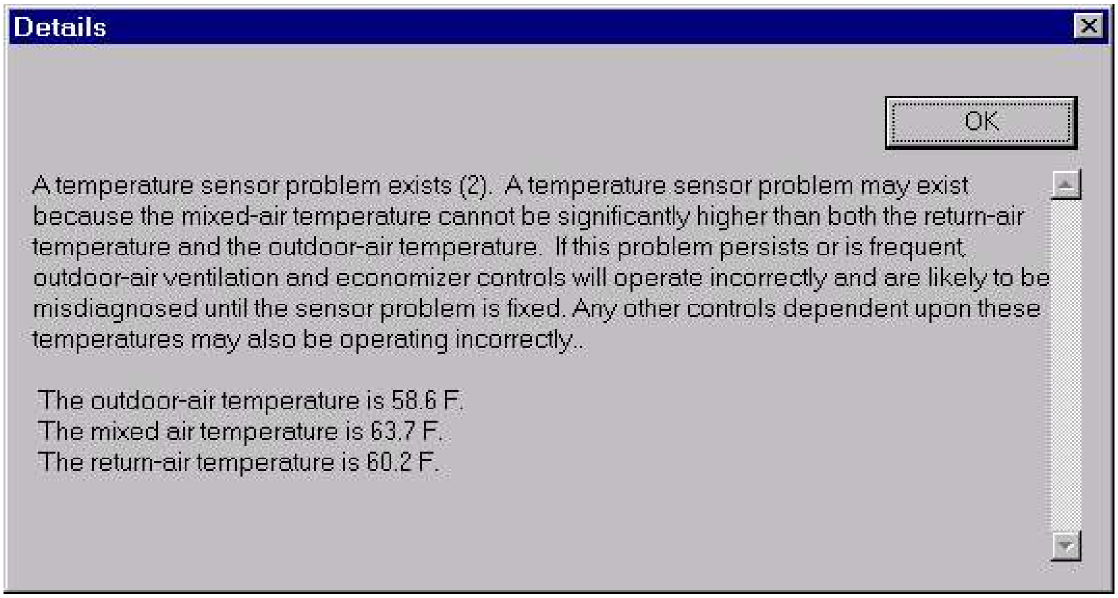


Figure 7 – "Details" Window Showing a Detailed Description of the Temperature Sensor Problem Identified in Figure 5

6.8 Requirements for Using the WBD and OAE

The WBD and its diagnostic modules were developed for a personal computer running any Microsoft Windows operating system (98/ME/NT/2000/XP)[4]. The WBD can be run in a fully automated/unattended mode or can be used to batch process the data. To run the WBD in a fully automated (unattended) mode, the data collection from the air handlers to the WBD database must be fully automated. A companion data collection module can be used to collect the data from air handlers that are controlled by central building automation systems. To use this data collection module, the site needs a networked computer operating under Windows 98/NT/2000 (preferably NT or 2000 to avoid problems with the computer's clock) and a building automation system (BAS) that supports Microsoft DDE protocols. There are other methods available for data collection; however, several of the current methods may require increased levels of human intervention (see Figure 1).

Although the underlying methodology used by the OAE is independent of the time interval at which data are collected, the user interface can only display results at hourly intervals. Therefore, all data should be at least at an hourly resolution. The data collection module can process data that is more frequent (5-minute intervals, for example) and average it to hourly values. Instantaneous values obtained on 5-minute intervals or less, and averaged to form hourly data, are recommended. It is preferable to have all measured data either instantaneous or averaged. Mixing instantaneous and averaged data may introduce false alarms and therefore is not recommended.

[4] Although the initial version of the WBD and its components were developed and tested under the Windows 95 operating system, this operating systems is not currently supported.

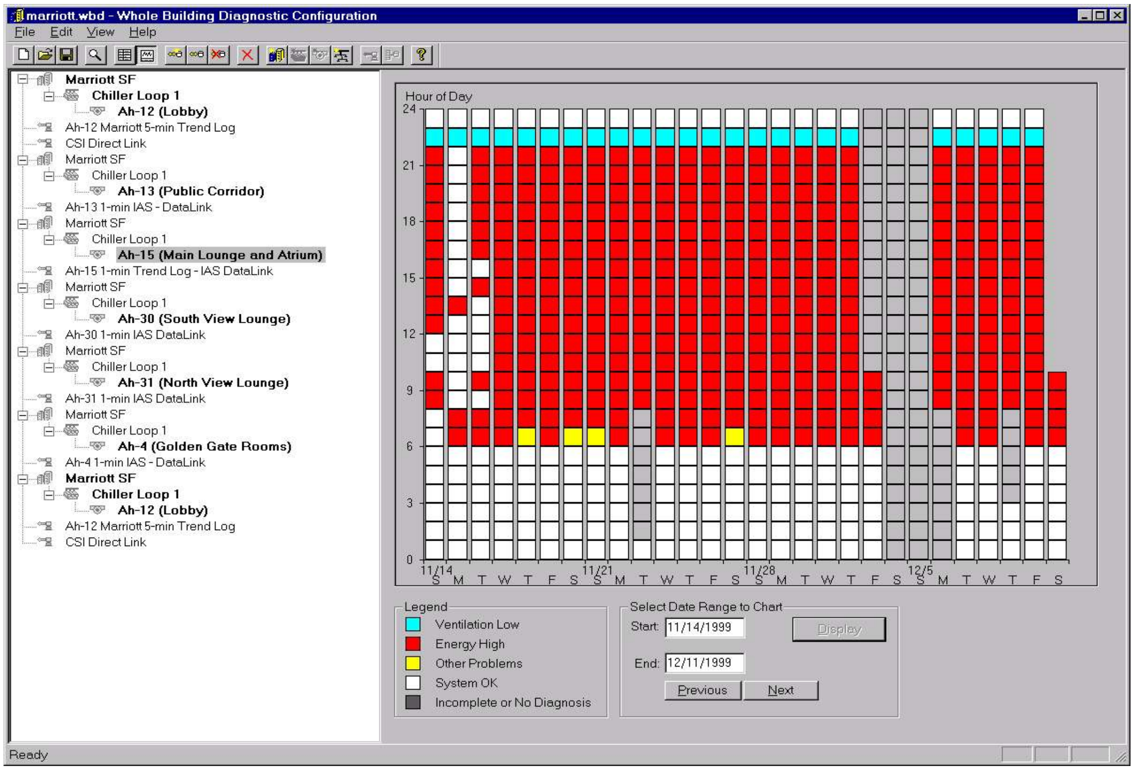


Figure 8 – An Example OAE display is shown for Air Handler 15 for November 14 through December 11. A high energy consumption problem is clearly evident throughout this time period.

7 Summary of Off-line Results for Symphony Towers

The data for the off-line tests for all four air handlers were collected using the trending feature of existing building automation system in Symphony Towers. The data were from December 10, 1999 through January 13, 2001 collected on 10-minute intervals, with only a couple 1- or 2-hour gaps (3 p.m. to 4 p.m. on February 8, 2001 and 12 p.m. to 1 p.m. on February 16, 2001). A typical section of the data after it was assembled into a single file is shown in Table 2. The column names are the sensor and control point names used in the Metasys control system. The data for the other three air handlers were similar.

The only problem with the data delivered for the off-line test was that the return-air enthalpy (computed by the control system) was provided in lieu of the return-air relative humidity that was requested. This was simply an oversight in setting up the trend logs for the test. Fortunately, the relative humidity could be computed from the enthalpy and temperature of the air using an Excel macro. This manual step completed the data set and allowed the off-line test to proceed normally.

Table 2 – Typical Raw 5-Minute Data from AHU-1

Day	Date	Time	-FAN%	-CHWV	-DAT	-RAT	-MAT	-OSA-T	-RAE	-OSA-EN	-ECON	-RAH	-OSA-RH
Mon	12/13/1999	9:10	82.5	100.0	63.3	76.1	56.8	54.9	23.6	20.1	100.0	25.7	67.5
Mon	12/13/1999	9:20	82.7	100.0	63.5	76.3	56.1	55.2	23.7	20.2	100.0	25.8	67.5
Mon	12/13/1999	9:30	82.8	100.0	63.6	76.2	56.8	55.2	23.7	20.4	100.0	26.0	67.5
Mon	12/13/1999	9:40	82.9	100.0	64.1	76.4	57.4	56.0	24.0	20.7	100.0	26.8	67.5
Mon	12/13/1999	9:50	83.6	100.0	64.4	76.5	58.0	56.3	24.0	20.8	100.0	26.7	67.6
Mon	12/13/1999	10:00	84.4	100.0	64.8	76.6	58.1	56.7	24.1	21.0	100.0	26.8	67.5

Table 2 Heading definitions:

-FAN% is the percentage of full fan operation at the current time
-CHWV is the percentage open for the chilled-water valve
-DAT is the discharge-air temperature for the air downstream of the cooling coil and supply fan
-MAT is the mixed-air temperature
-OSA-T is the outdoor-air temperature
-RAE is the return-air enthalpy
-OSA-EN is the outdoor-air enthalpy
-ECON is the percentage of fully open for the current outdoor-air damper position (100 corresponds to the maximum economizing possible)
-RAH is the return-air relative humidity
-OSA-RH is the outdoor-air relative humidity.

7.1 Configuring the Diagnostician

The next step in conducting the off-line analysis was to specify the air handler's configuration for the WBD's OAE diagnostic module. There are two aspects of the air handler's operation that must be specified for the OAE: the control strategy for the outdoor-air and economizer, and the schedule (times of day and days of week) for which the minimum outdoor air must be supplied for the occupants.

The configuration screen of the WBD's user interface is shown in Figure 9. The left side is the hierarchical "configuration tree" specified by the Administrator for this WBD installation. In this case there is the Symphony Towers building and a data collection network, which is repeated four times at the highest level. This is because data for each air handler is stored in a separate database for convenience. Beneath the building is a heating/cooling plant, and the plant serves the air handlers. In the off-line test only one air handler (AHU-1) is configured. When the user selects AHU-1 and the configuration tab on the toolbar is pushed, as shown, the configuration for AHU-1 is displayed as shown.

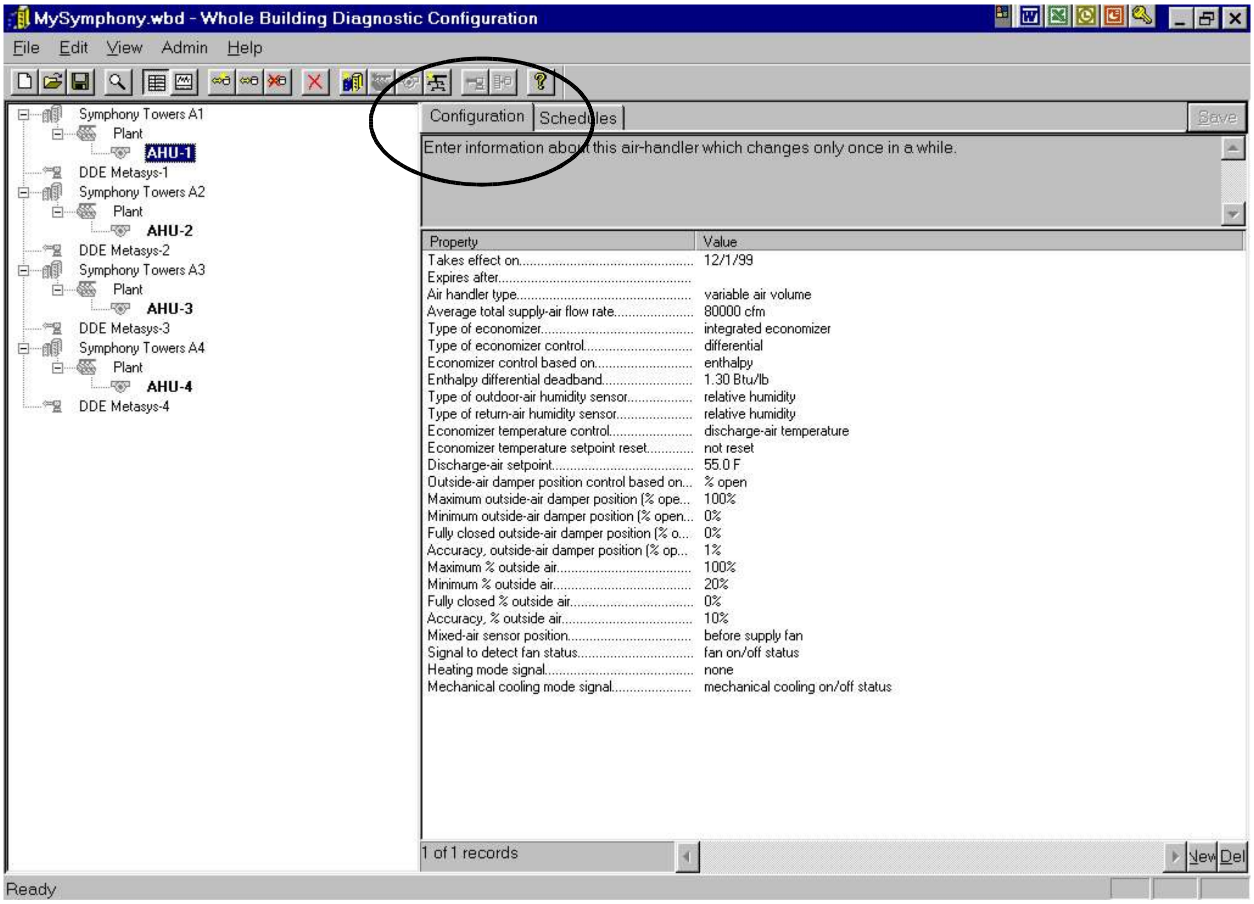
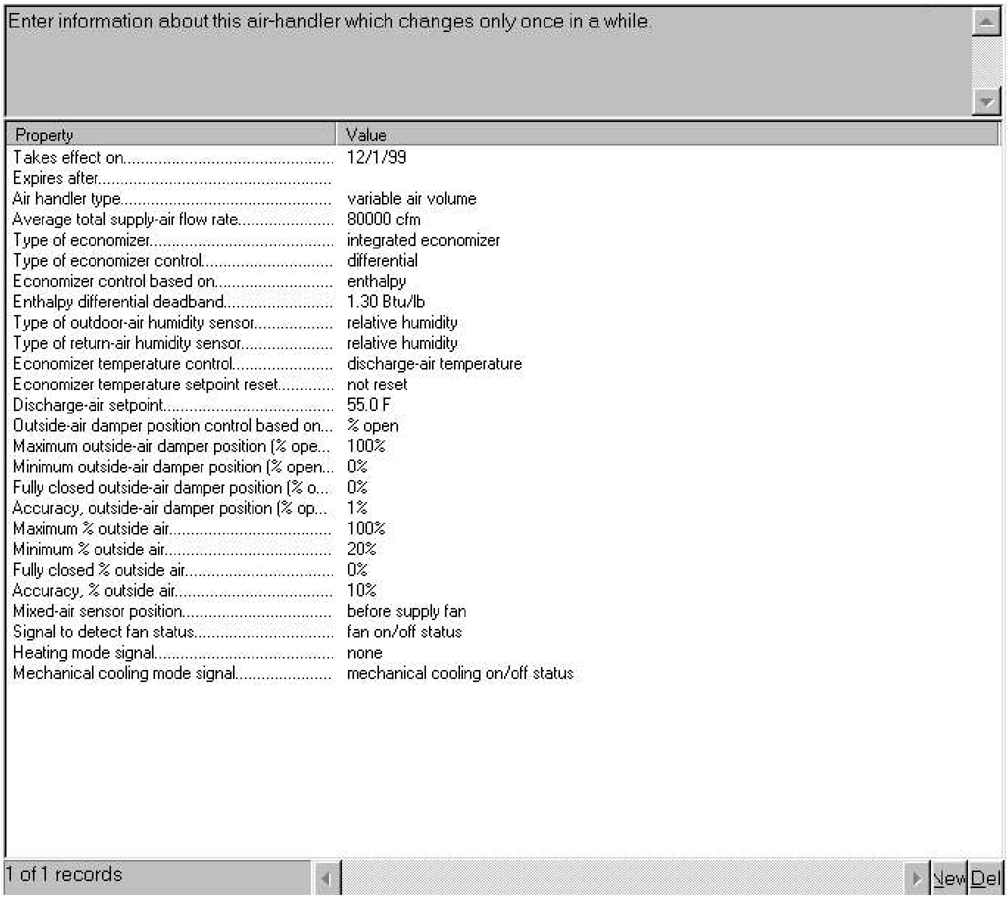


Figure 9 – WBD's Air Handler Configuration Screen for AHU-1

7.2 Air Handler Configuration Parameters

The configuration parameters for AHU-1 are shown in Figure 10. The AHU is a variable-air-volume type with a maximum air flow rate of about 80,000 ft^3/min. It has an integrated economizer with control based on the differential between the return- and outdoor-air enthalpies, computed from dry-bulb temperature and relative humidity measurements. The dead band for economizer operation is 1.3 Btu/lb[5]. AHU-1 has a constant discharge-air temperature set point of 55^{o}F.

[5] Dead bands are usually specified in the control system to avoid excessive cycling for the outdoor-, return- and exhaust-air dampers. For temperature-based economizers, it is typically between 1^{o}F and 2^{o}F; for enthalpy economizers, it is between 1 and 2 Btu/lb.



Enter information about this air-handler which changes only once in a while.

Property	Value
Takes effect on	12/1/99
Expires after	
Air handler type	variable air volume
Average total supply-air flow rate	80000 cfm
Type of economizer	integrated economizer
Type of economizer control	differential
Economizer control based on	enthalpy
Enthalpy differential deadband	1.30 Btu/lb
Type of outdoor-air humidity sensor	relative humidity
Type of return-air humidity sensor	relative humidity
Economizer temperature control	discharge-air temperature
Economizer temperature setpoint reset	not reset
Discharge-air setpoint	55.0 F
Outside-air damper position control based on...	% open
Maximum outside-air damper position (% ope...	100%
Minimum outside-air damper position (% open...	0%
Fully closed outside-air damper position (% o...	0%
Accuracy, outside-air damper position (% op...	1%
Maximum % outside air	100%
Minimum % outside air	20%
Fully closed % outside air	0%
Accuracy, % outside air	10%
Mixed-air sensor position	before supply fan
Signal to detect fan status	fan on/off status
Heating mode signal	none
Mechanical cooling mode signal	mechanical cooling on/off status

1 of 1 records New Del

Figure 10 – Configuration Parameters for AHU-1

The outdoor-air damper system is controlled based on a specification of damper position (% open), with a minimum position the same as the fully-closed position (0%) and a maximum position of 100% during economizer operation. The minimum outdoor-air fraction is expected to be about 20% when the fan is operating because one bank of outdoor-air dampers is intentionally disconnected from the actuator and left in the open position to ensure minimum outdoor air is always supplied. The damper position is assumed accurate to within 1%. The maximum damper position was specified as corresponding to an outdoor-air fraction of 100%. The resulting outdoor-air fractions computed by the OAE diagnostic module from the air temperatures were observed to be accurate to within about 10%.

The remaining parameters specify the types of signals and thresholds used to determine whether the supply fan and heating and cooling modes for the air handler are on at a given time. The other air handlers at Symphony Towers are configured similarly.

7.3 Off-line Test Results

The OAE diagnostic results for the first 28 days of the off-line analysis are shown in Figure 11. This view is displayed when the user selects AHU-1 on the configuration tree on the left side of the screen and pushes the *View diagnostic results* button on the toolbar. Each square of the "checkerboard" displays the diagnostic result for an hour, and each column of squares provides results for all hours in 1 day. Each square is color coded to indicate the general category of problem identified that hour, if any. As indicated in the legend in the lower part of the display, white squares indicate normal operation without problems (more strictly, no fault was detected). This was seldom the case for AHU-1 during this time. Gray squares indicate that full diagnosis could not be completed, generally when outdoor- and return-air temperatures are too close for an accurate outdoor-air fraction to be computed. Gray squares also are used to indicate missing data.

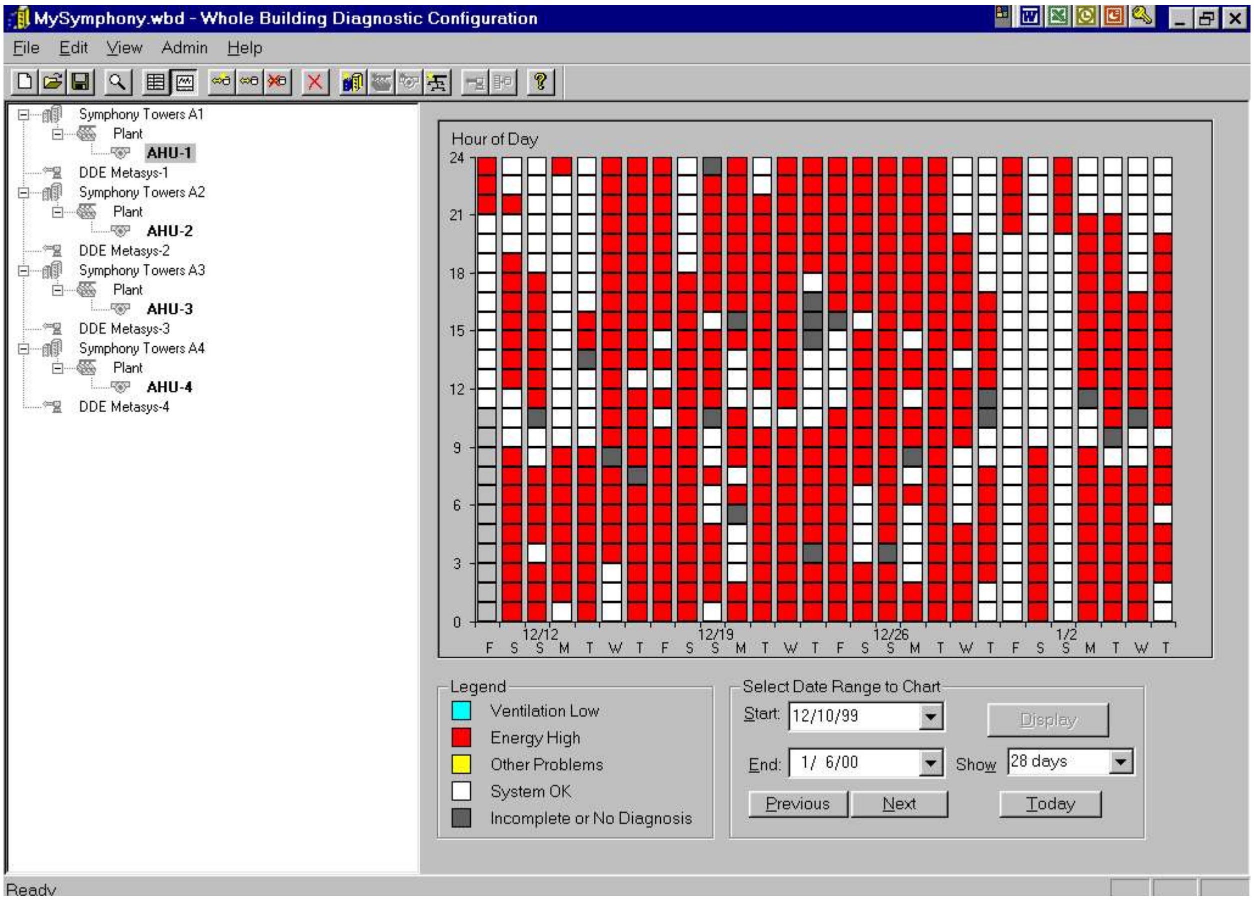


Figure 11 – Display of OAE Diagnostic Results for AHU1

Colored cells indicate abnormal or faulty operation. Blue squares indicate inadequate outside ventilation air is being supplied for the occupants; no problems of this type were detected during the period of the analysis.

The numerous red squares indicate problems that wasted energy. As indicated in Table 3, there are two general problems that occurred over 60% of the time during the period analyzed. They are investigated in further detail here. The information given in Table 3 is not displayed by the OAE, but a user can get a sense for the frequency of problem detection by sampling the cells in the OAE display. Last column in Table 3 represents the reliability score, which is cumulative uncertainty calculated from propagating the measurement uncertainty of measured values and user defined values.

Table 3 – Frequency of the Problems for AHU-1 (the color of the various categories match the color code from the OAE diagnostic tool)

Category of Operational States	Number of Occurrences	Percent of Total Occupied Hours (%)	Reliability Score
Control Problems	0	0%	NA
Excess Ventilation	315	39%	86%
Low Economizer Flow	32	4%	93%
Control Problems	166	20%	95%
Inadequate Ventilation	0	0%	NA
OK but incomplete diagnosis	24	3%	93%
Operation OK	273	34%	53%

Clicking on the first red cell (hour 22 [10 p.m.] on Friday December 10, 1999) displays the *Current Condition* dialogue shown in Figure 12. The problem is indicated as mechanical cooling is on but should be off. By browsing the other red squares, it was found that this message is common to many of them. This is a control problem that wastes energy (red control problem in Table 3), and it occurs 20% of the time during this period, as shown in Table 3. The cost impact estimate for this hour is modest, an estimated $5/hour for excess cooling at an average electricity price (including demand charges) of $0.15/kWh. A number of possible causes for this problem are presented; clicking on one of them (as shown) produces guidance to the operator in the form of suggested action(s) that might be taken to verify and correct the problem.

Clicking on the *Details* button provides additional information on the nature of the problem, as shown in Figure 13. This provides a more detailed description of the problem, and some key data that led to identification of this problem (and potentially for an experienced investigator to help interpret it). The economizer is operating only fully open, because the mixed-air temperature is about equal to the outdoor-air temperature. But mechanical cooling is on, even though the mixed-air temperature was quite cool at 54°F, below the supply-air temperature set point of 55°F and should have been cool enough for the economizer to provide all the necessary cooling. The cause of this problem was not isolated (four possible causes are given), and the operation and maintenance staff would need to visually check all potential causes to isolate the actual cause. As we show in Section 7.4, additional information could be obtained by examining trends in the raw data (but the OAE diagnostician does not yet automate the process to this depth).

Browsing the red squares also showed another type of problem was even more prevalent during the period (39% of the time) of the off-line analysis. Clicking on one of the red squares occurring during the afternoons (hour 16 [4 p.m.] on Sunday December 12, 1999) provides the *Current Condition* shown in Figure 14 and the *Details* shown in Figure 15. These displays indicate that even though the damper position is correct, the resulting outdoor-air fraction is too high. This excess outdoor air has a large cost impact: $76/hour for the hour being examined, which projects to $13,000 per week if those operating conditions persisted for every hour during that week.

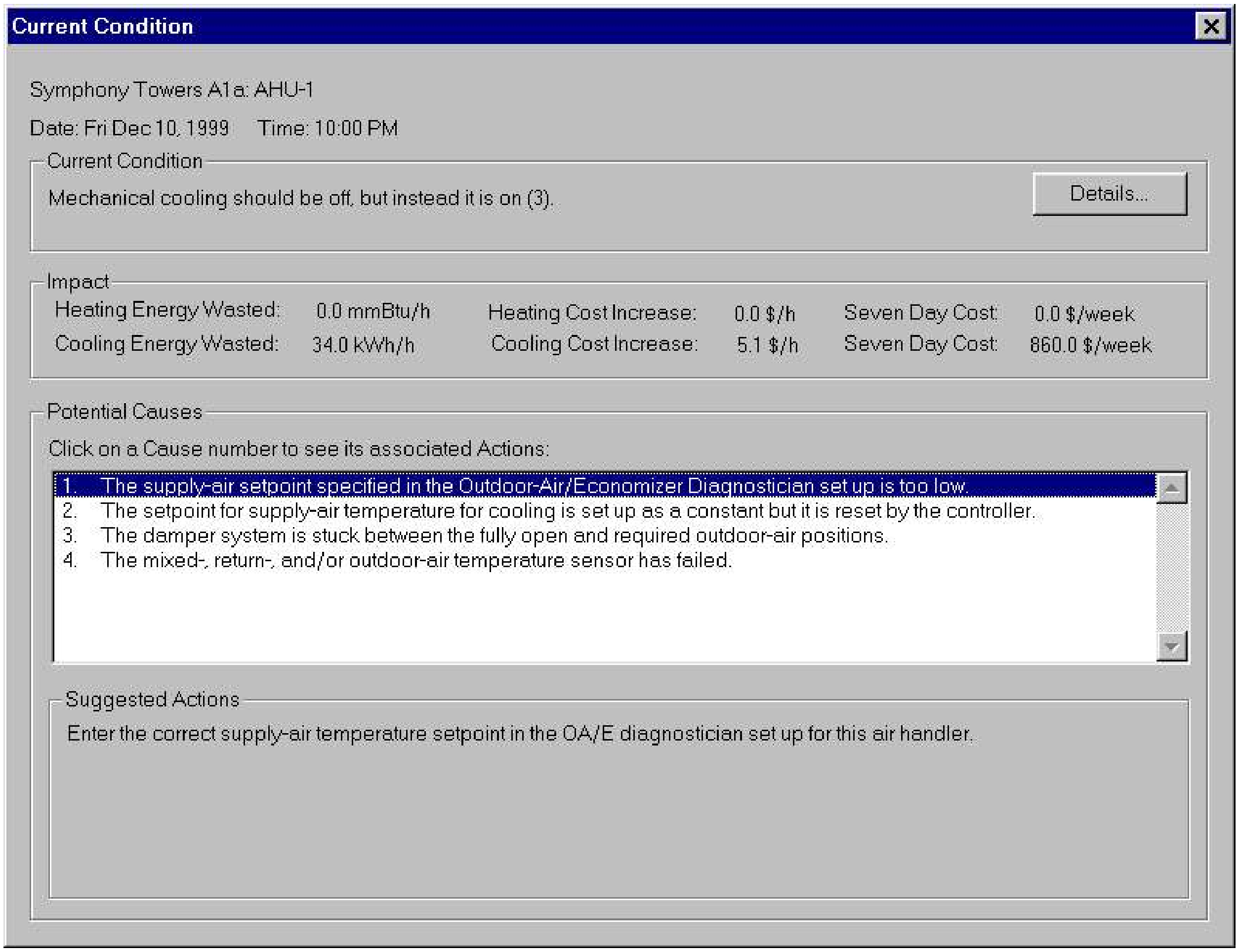


Figure 12 – Current Condition Dialogue for the Control Problem at 10 p.m. on Friday, December 10, 1999.

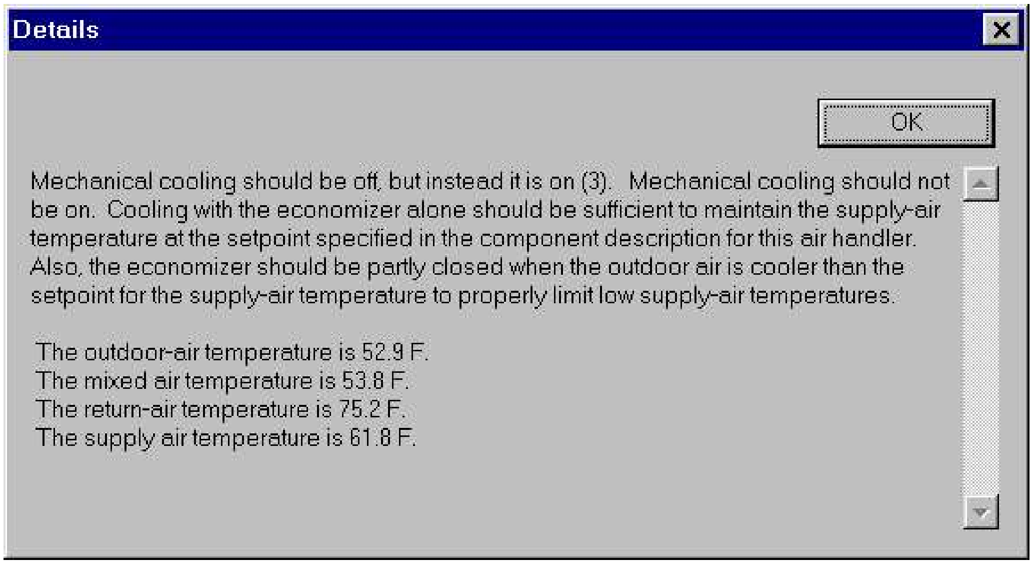


Figure 13 – Details on the Current Condition for the Control Problem

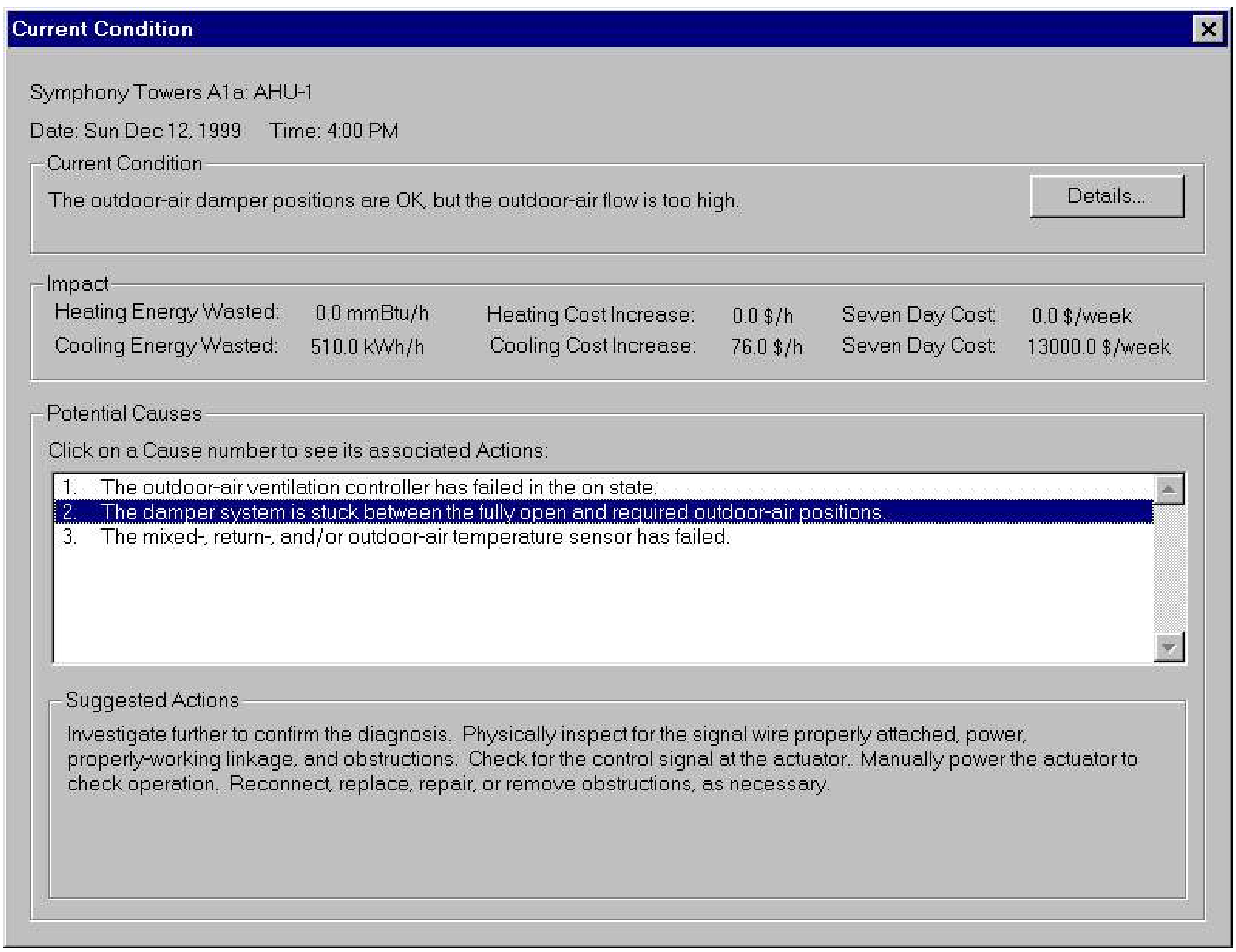


Figure 14 – Current Condition Dialogue for the Excess Ventilation Problem

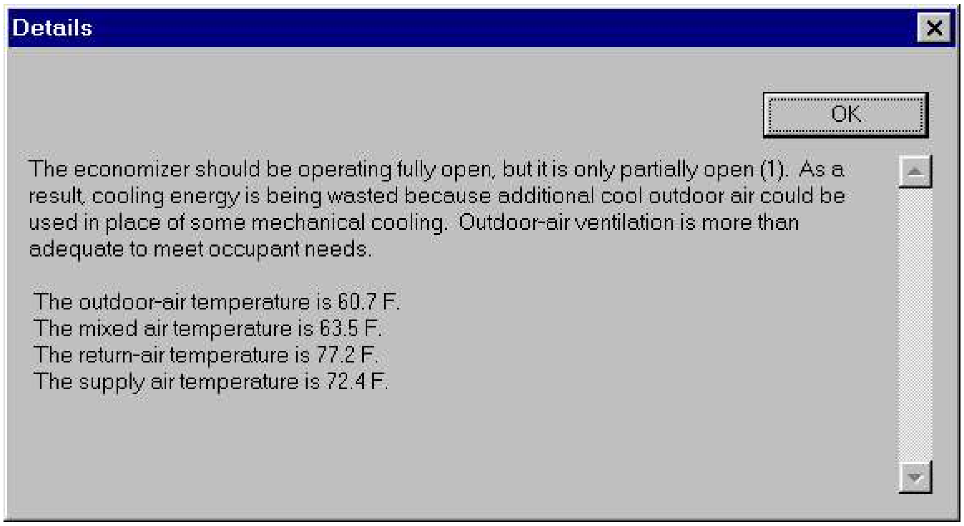


Figure 15 – Details Dialogue for Excess Ventilation Problem

7.4 Analysis of Trend Data

The user of the WBD is encouraged to examine the equipment or to utilize the control system's capabilities to investigate problems further when their exact cause or impact of a problem is unclear (i.e., a single cause is not isolated). In the off-line analysis for this project, our version of this is to look at the raw data, which in fact is identical with trend-log data obtained from the control system, to try to extract information beyond that provided by the OAE.

Examining the trend data showed that when the economizer was not running and the outdoor-air dampers were at their minimum position (0%), the outdoor-air fractions were in the range of 50% to 60%. Thus, it appears that too large a portion of the damper was disengaged from the actuator to maintain the desired 20% outdoor-air fraction and is allowing much more outdoor air than that to enter. Alternatively, it may be that the remainder of the damper system leaks more than expected or is not controlled properly to fully close (and this must be determined by visual inspection).

Examining the trend data also showed that when the control problems were indicated, the supply-air temperature exceeded its set point of 55ºF, and the chilled-water valve was continually at 100% in an attempt to maintain it. The reason for this was not clear until the pattern of supply-air temperature was examined in conjunction with Symphony Towers' controls consultant. The supply-air temperatures were consistently about 8ºF to 10ºF higher than the mixed-air temperature. Because the mixed-air temperature is checked by the OAE diagnostic module for consistency with the outside- and return-air temperatures, it was considered reliable. The supply-air temperature was then checked manually and found to be inaccurate. It was recalibrated. This adjusted its reading by about 8ºF higher than previously.

The whole HVAC system immediately began to unload as soon as this change was made. The control system data showed the chilled water valves immediately closed, and the fan speed increased as the terminal unit (VAV box) dampers opened, no longer trying to restrict entry of unwanted cool air. Undoubtedly significant reheating of this air was occurring in the terminal units. The WBD's display of problems after this correction is shown in Figure 16. Note that the frequency of problems is greatly reduced.

This problem is not the focus of the OAE diagnostic module because it is a more general air handler problem outside the OAE's scope. Nevertheless, the problem was detected by the OAE diagnostician under conditions when it affected the economizer function. Its actual impacts are difficult to assess and are the subject of a supplementary analysis being conducted. The case, however, is a good example of how the OAE can identify problems and their potential causes. Building staff can then follow up to examine these problems carefully, isolate the causes, and correct them to capture energy savings and improve building performance.

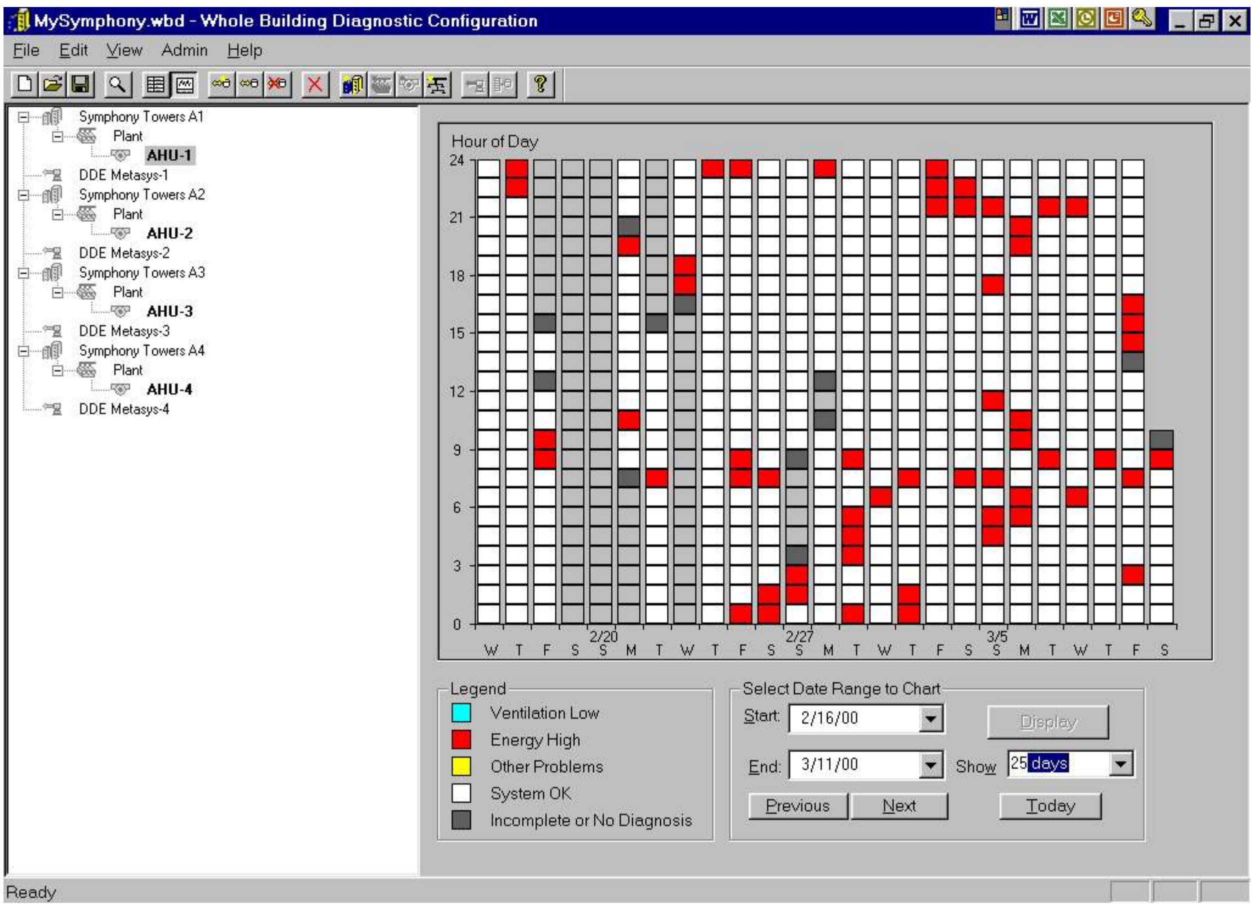


Figure 16 – WBD Display of Problems after Supply-Air Temperature Sensor was Fixed

7.5 Conclusions from Off-line Tests

Two problems were found in the operation of AHU-1 in Symphony Towers. One, unnecessary cooling as a result of the uncalibrated supply-air temperature sensor, was fixed immediately after the off-line analysis was completed. The second problem, the outdoor-air flow rates at the minimum occupied level being too high, should be corrected by adjusting the flow rates downward to save energy while still providing sufficient outdoor air to maintain indoor-air quality. This second problem is only an issue during the heating season or times when it is too hot for the economizer to open. Fortunately, San Diego's mild climate minimizes the impact of this problem.

No problems were detected with the primary temperature sensors (return-, outside-, and mixed-air). This suggests that the sensors are providing reasonably-accurate data. Symphony Towers had recalibrated these sensors before the WBD demonstration. The supply-air sensor did not receive this calibration, however, and was to be found faulty.

8 On-line Data Collection and Testing

Continuous data collection and testing started immediately after the off-line test was completed and the WBD configured for all four AHUs in April 2000 and continued through the end of the demonstration project March 2003.

8.1 Data Collection

The automated on-line data collection uses the Dynamic Data Exchange (DDE) protocol, an industry standard protocol developed by Microsoft, for exchanging data between two applications. The DDE server application developed by the control manufacturer [in this case Johnson Controls Inc. (JCI)] only runs on an operator's workstation; therefore, a part of the WBD's data collection software also had to run on the workstation. Although the entire WBD software can run on the operator's workstation, at Symphony Tower most of the WBD software was on a separate workstation, as shown in Figure 17.

The WBD periodically requests data from the BAS through the operator's workstation using the TCP/IP network. Requests from the WBD are acknowledged by the WBD's data acquisition module that runs on the operator workstation, which in turn passes those requests to the BAS through an intermediate application (Metalink from JCI). Metalink gets the data from sensors or control devices and passes it to the WBD, which stores them in a Microsoft Access database for processing. The data requests can be made at any frequency. At Symphony Towers, the data was requested at 5-minute intervals and integrated over the hour before being processed by the diagnostic module.

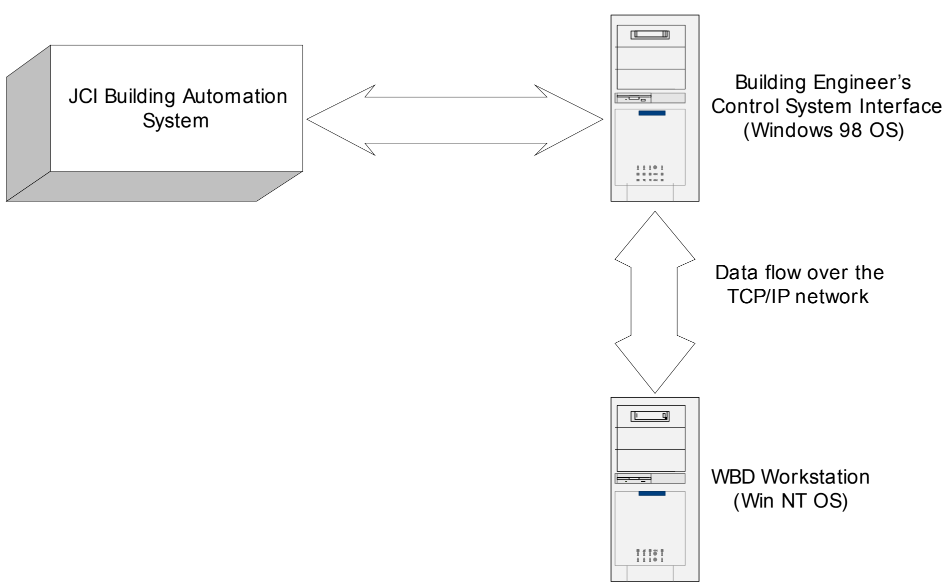


Figure 17 – Schematic diagram of the On-line Data Collection Process at Symphony Towers

The list of data points for each of the four AHUs at the Symphony Towers is shown in Table 4. Integration of most channels is conditioned on whether the fan is on, as shown in Table 4.

As noted earlier, the automated on-line data collection started in April 2000 for all four AHUs. The data collection module on the operator's workstation and all modules for the WBD on the WBD workstation were put in the startup folder of the respective workstations so that when the computers were rebooted, all necessary software was automatically initiated. However, if applications are manually terminated, the data collection process stops until the application is manually restarted or until the workstation is restarted. There were several occasions where the data acquisition module on the operator's workstation was manually terminated and it went undetected for several weeks. Although several weeks of data were lost as a result of this problem, more than 1 year of data was collected for all four AHUs.

Table 4 – Data Points Collected by Symphony Towers for OAE Diagnostic Module

Type of Data	Data Item	Units	Integration
time stamp	time stamp (end of hour)	Date Time	none
fan on-time	fan on-time	Fraction	average hourly
air temperatures	outdoor-air (dry-bulb) temperature	°F	average hourly when fan on
	return-air (dry-bulb) temperature		
	mixed-air (dry-bulb) temperature		
	supply-air temperature (dry-bulb)		
air humidities	outdoor-air relative humidity	%	average hourly when fan on
	return-air relative humidity		
damper position	outdoor-air damper position command	% open	average hourly when fan on
status of AHU	chilled-water valve position (fraction open)	% open	average hourly when fan on

8.2 Results for AHU-1

Initially, when the off-line data from AHU-1 was processed, most of the cells were red, indicating energy waste (Figure 11). The OAE diagnostician identified that the problem was related to the supply-air temperature. During a site visit, the diagnosis was confirmed and the supply-air temperature recalibrated. After the recalibration, the number of red cells decreased considerably (Figure 16) but were not totally eliminated. Red cells remained because the AHU is drawing in more outdoor air than required to meet the ventilation requirement when conditions are not favorable for economizing and when the AHU is in the heating mode.

By design, the OAE diagnostician's single-state diagnostic process terminates and reports a finding that the AHU is improperly operating when it finds the first problem (for a particular hour). Although the process could be modified to track multiple problems simultaneously, the computational overhead of doing so would certainly be higher than for the single-state process that the OAE currently uses. If the AHU has multiple problems, like AHU-1, the process only identifies the first predominant problem encountered. However, if the first problem is corrected and new data are then analyzed, the OAE will identify the next predominant problem encountered or will indicate no problems if all problems have been fixed. Identifying faults sequentially may take slightly more time, but it is still better than letting the AHU operate inefficiently or in faulty condition without the operation staff knowing.

The second problem (excess outdoor-air) for AHU-1 continued through the on-line monitoring period, as seen in Figure 18 and Figure 19. It is important to note the number of red cells in

Figure 18 is greater than in Figure 19. This is caused by differences in outdoor conditions during the two periods. In September and October, outdoor conditions are less favorable for economizing compared to conditions in December and January (in San Diego). When the AHU is not economizing, the damper is at the minimum position, and it is during these conditions that this fault manifests itself.

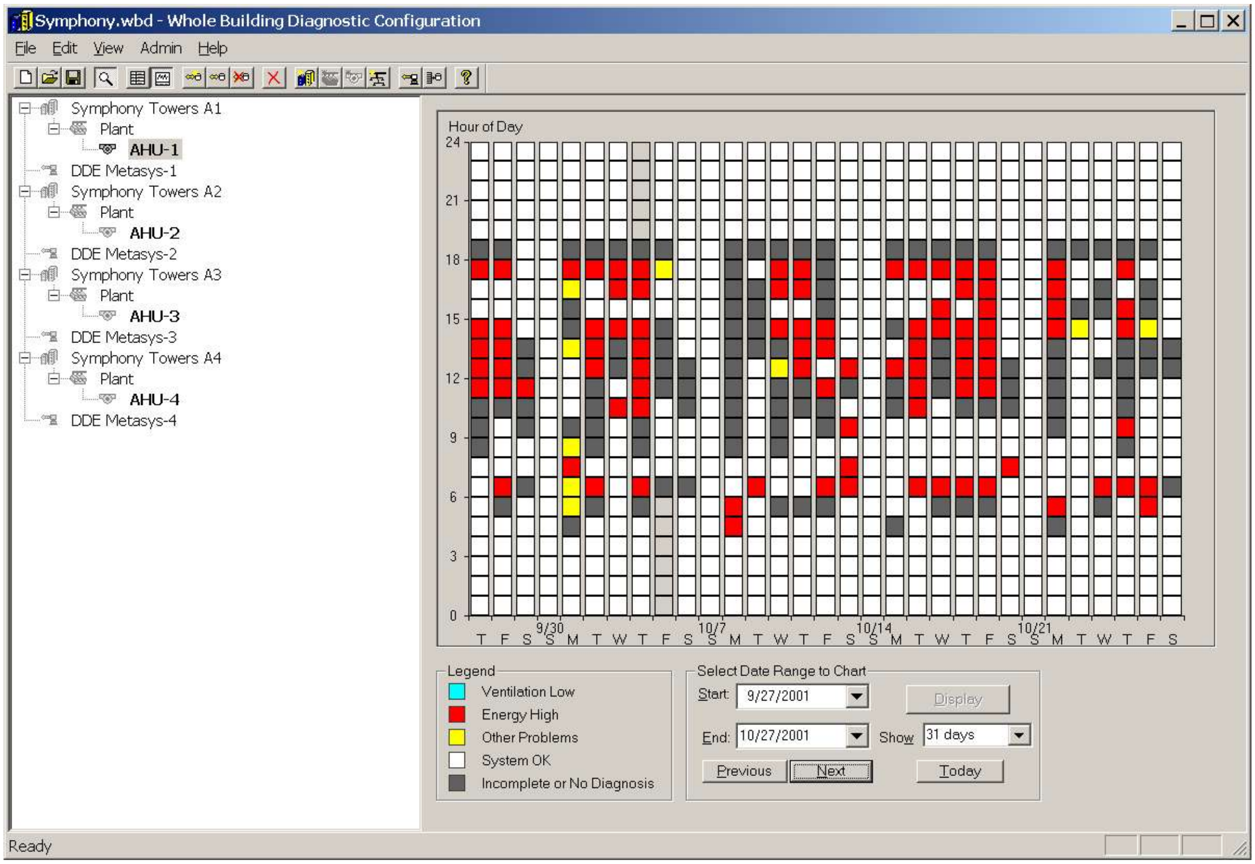


Figure 18 –WBD Diagnostic Results for AHU1 for a Period from September 27 through October 27, 2001

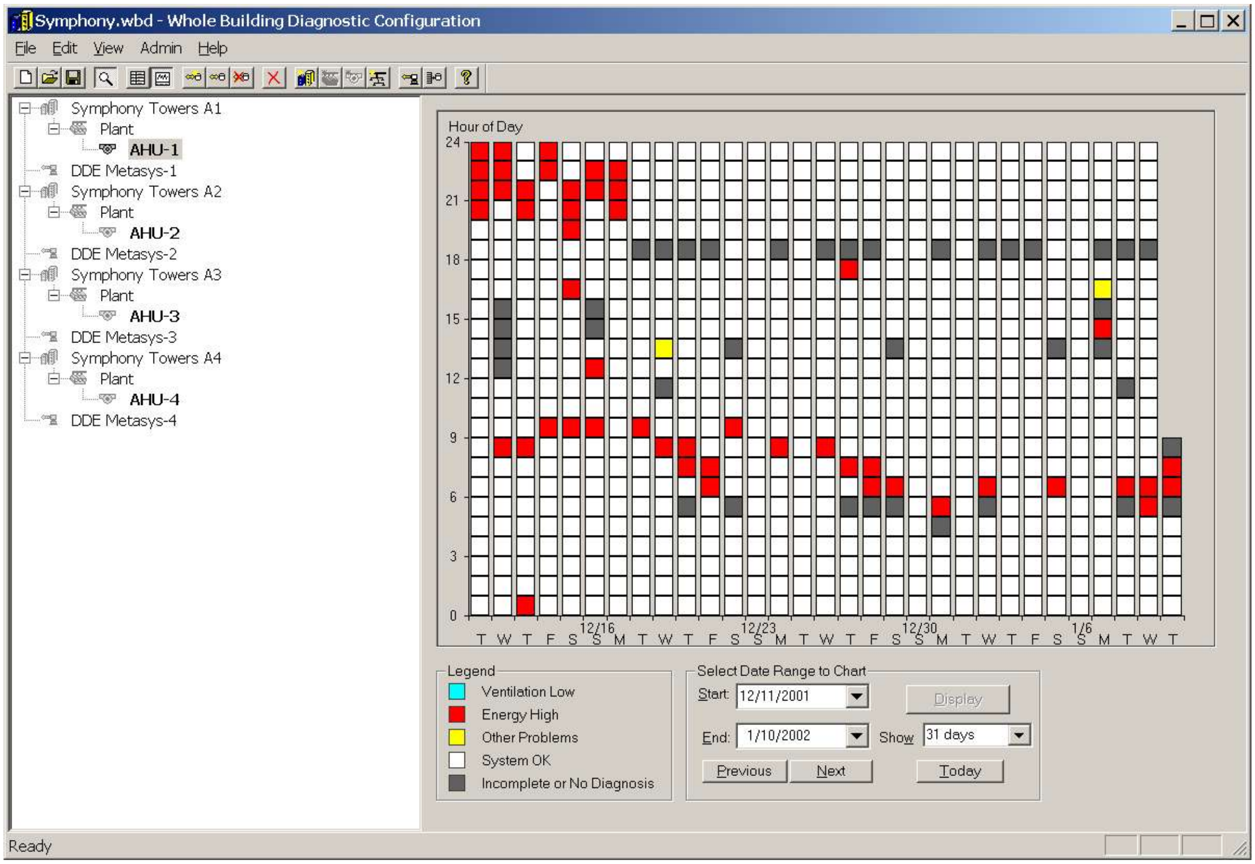


Figure 19 –WBD Diagnostic Results for AHU1 for a Period from December 11, 2001, through January 10, 2002

The frequency of problems reported during the on-line test (March 2001 through January 2003) after the correction of the first problem (supply-air temperature sensor calibration) is shown in Table 5. Compared to frequency the distribution prior to correcting the first problem identified (Table 3), the percentages of excess ventilation and control problems have decreased, while the percentage of hours when the diagnosis was incomplete has increased substantially.

Table 5 – Frequency of the Problems for AHU-1 when the Building is Occupied (March 2001 through January 2003)

Category of Operational States	Reliability Score	Number of Occurrences	Percent of Total Hours (%)
Control Problem	0.933	119	2.5
Control Problem – Excess Energy	0.946	156	3.3
Excess Ventilation	0.863	862	18.2
Low Economizer Flow	0.934	175	3.7
Inadequate Ventilation	0.855	2	0.0
OK but incomplete diagnosis	0.934	890	18.8
Operation OK	0.562	2522	53.4
Total		**4,726**	**100**

8.3 Results for AHU-2

In April 2000, the WBD was set up to automatically collect and process data from AHU-2 continuously through the end of the demonstration period. Like AHU-1, there were several gaps in data from AHU-2, again, primarily caused by manual termination of data collection software on the operator's workstation.

The results from the WBD indicate that AHU-2, like AHU-1, is operated improperly. The screen shot of the processed results for the time period between June 1 and July 1, 2000, is shown in Figure 20. A significant number of cells during occupied hours (6 a.m. to 9 p.m.) are yellow, followed in frequency by grey and blue. Yellow and blue cells, in most cases, indicate a problem with the temperature sensors (outdoor-air, return-air or mixed-air). Clicking on one of the yellow cells (hour 13 on June 20, 2000) displays the *Current Conditions Dialogue* shown in Figure 21. This indicates the presence of a temperature-sensor problem. By browsing the other yellow cells, this message was found to be common to almost all of them. The cost impact shown in Figure 21 is meaningless because it was based on a faulty sensor value. The OAE diagnostician cannot accurately estimate energy and cost impacts from fault temperature data.

Clicking on the *Details* button (shown in Figure 21) provides additional information on the nature of the problem, as shown in Figure 22. This provides a more detailed description of the problem, and some key data upon which detection of the problem is based. This data can also help understand the problem better. The mixed-air temperature (78.4 ^{o}F) is higher than both the return-air (76.4 ^{o}F) and outdoor-air (71.2 ^{o}F) temperatures. Although the OAE diagnostician has detected a problem with the temperature-sensor data, it cannot isolate which of the three sensors is faulty. Examination of the trend data, however, may provide additional information that may allow for isolation of the fault (but this is not yet implemented in the OAE).

The most current results (at the time of writing this report) are shown in Figure 23; they are similar to the results shown in Figure 21. Although there are more red cells compared to the earlier time period, browsing the cells reveals the potential cause is still same, a temperature-sensor problem.

The frequency of problems reported for AHU-2 is shown in Table 6 (March 2001 and January 2003). The AHU-2 operates almost 30% of the occupied period with a control problem, 11% with inadequate ventilation and 9% with low economizer flow (economizer not fully open). Although the temperature-sensor problem exists at all times, it only manifests about 50% of the time, during the occupied hours.

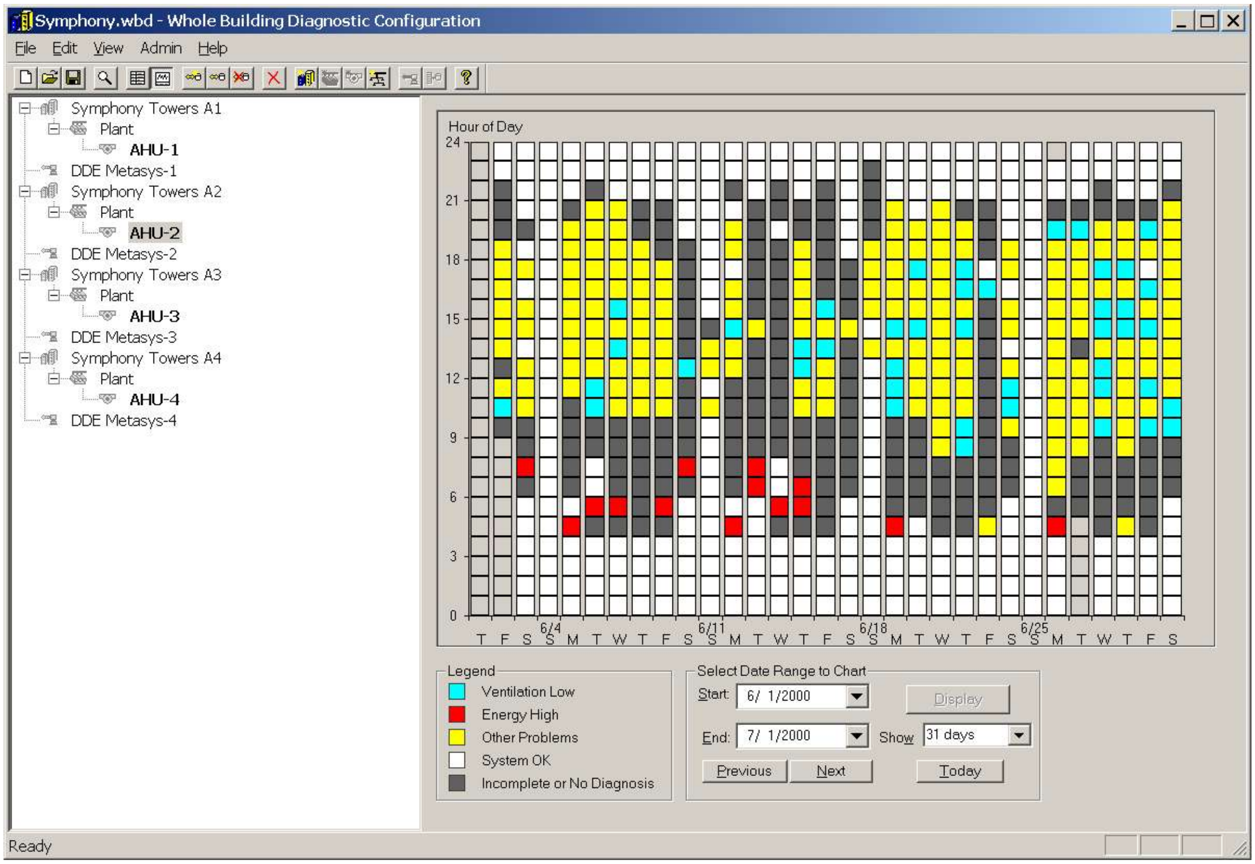


Figure 20 – WBD Diagnostic Results for AHU-2 for a Period from June 1 through July 1, 2000

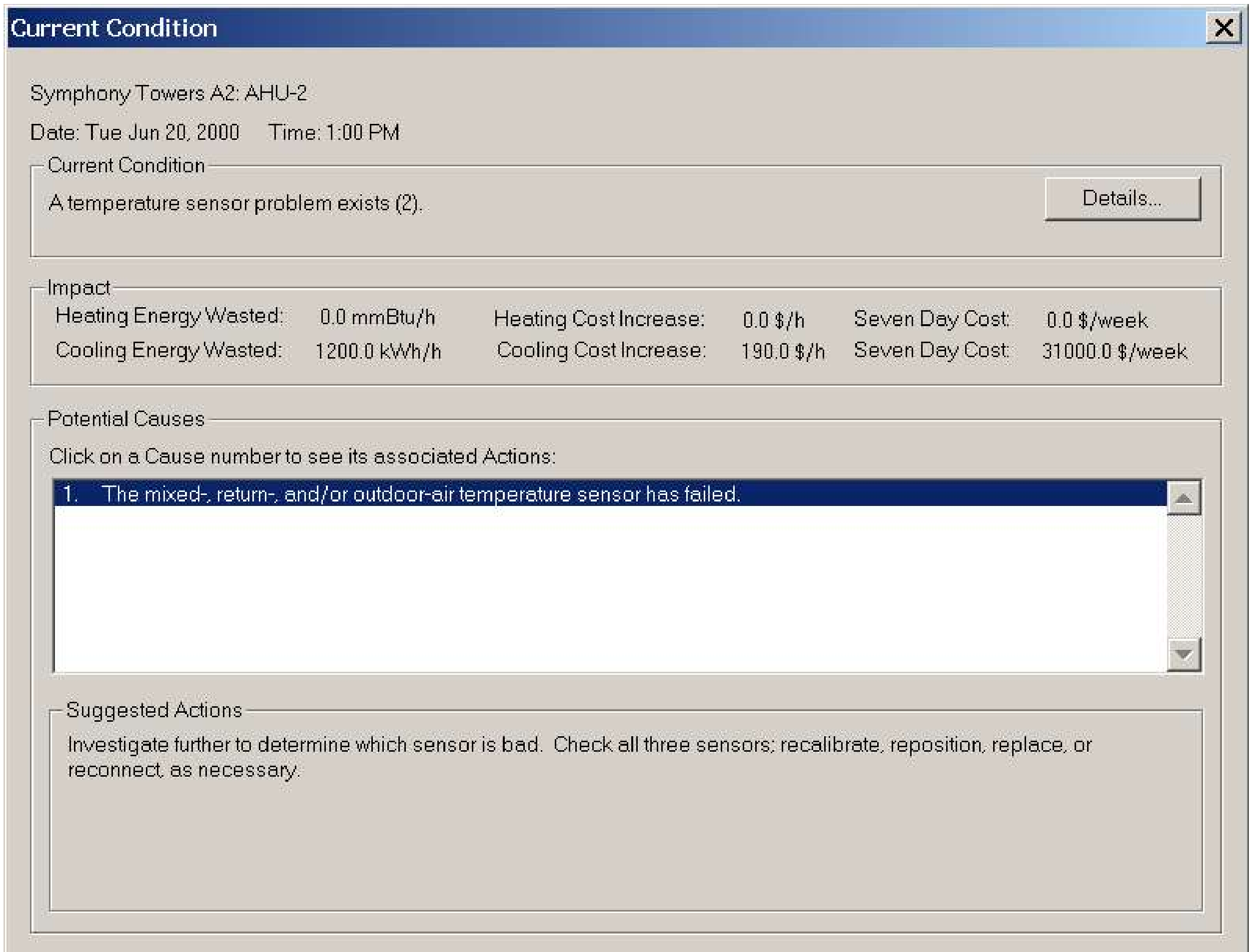


Figure 21 – Current Conditions Dialogue for AHU-2 for June 20, 2000, Indicating a Temperature-sensor Problem

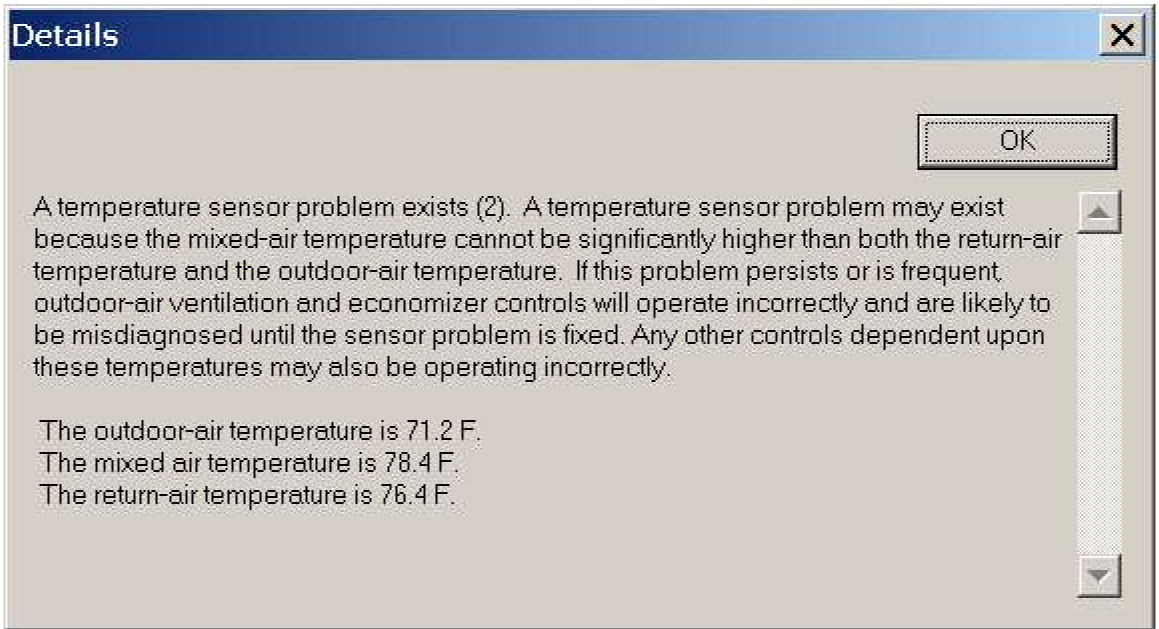


Figure 22 – Details Dialogue for AHU-2 on June 20th, 2000

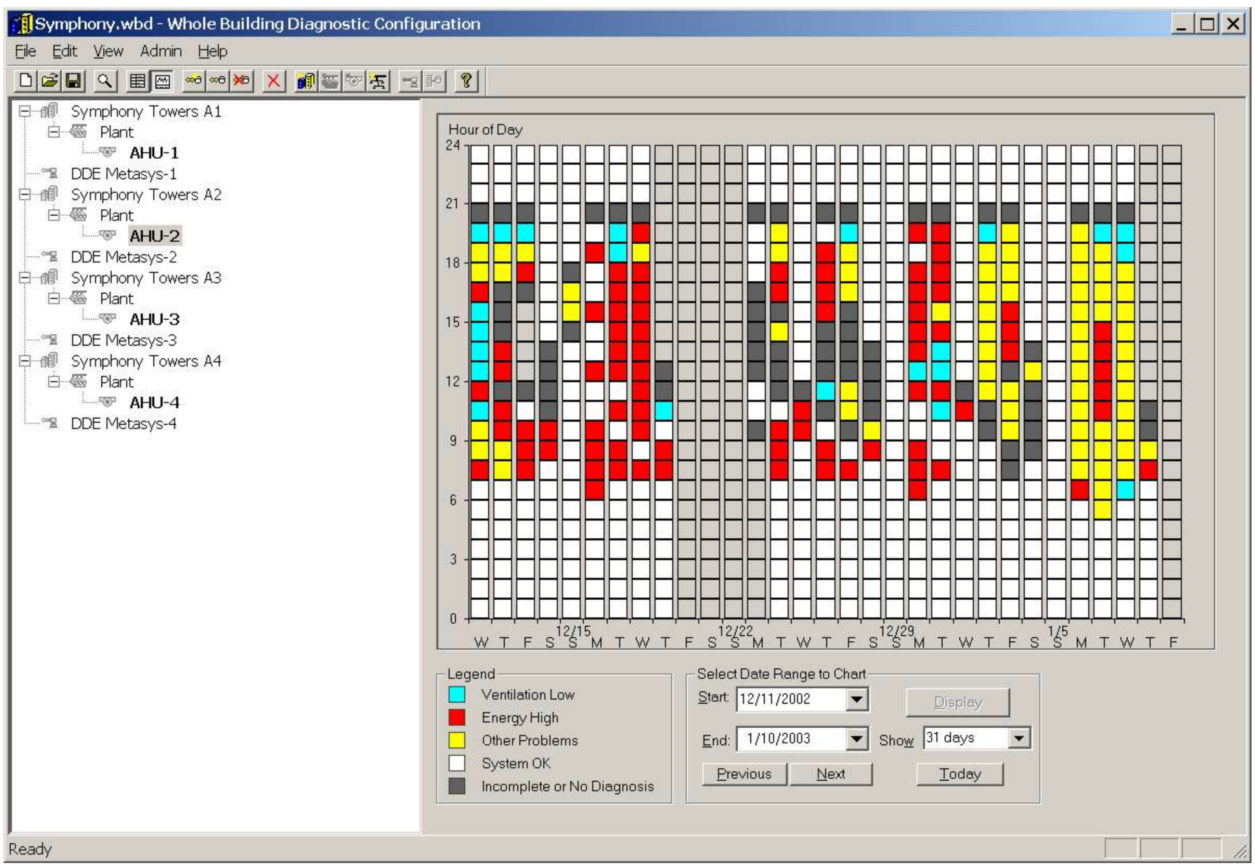


Figure 23 – WBD Diagnostic Results for AHU-2 for the Period from December 11, 2002, through January 10, 2003

Table 6 – Frequency of the Problems for AHU-2 when the Supply-Fan was Operational (March 2001 through January 2003)

Category of Operational States	Reliability Score	Number of Occurrences	Percent of Total Hours (%)
Control Problem	0.872	998	26.5
Control Problem – Excess Energy	0.950	99	2.6
Excess Ventilation	0.859	43	1.1
Low Economizer Flow	0.800	323	8.6
Inadequate Ventilation	0.885	404	10.7
OK but incomplete diagnosis	0.940	1,343	35.7
Operation OK	0.614	549	14.6
Total		**3,759**	**100**

8.4 Additional Analysis of Data from AHU-2

The analysis presented in this section is not provided by the OAE, but could be undertaken by an engineer experienced in this sort of analysis. It is not expected that most users will undertake such analysis, but they will rather inspect the sensors directly to determine the sources of the problems found by the OAE diagnostician. The analysis is presented here (and in Sections 8.7 and 8.9) to provide more insight into the specific underlying problems that led to the findings of the OAE.

The OAE diagnostician detected a temperature-sensor problem but was unable to diagnose which of the three sensors was faulty. Additional graphical analysis presented in this section may provide addition information regarding which sensor is faulty. This graphical analysis is not part of the OAE module. In Figure 24 the mixed-air temperature is plotted as a function of the outdoor-air temperature when the outdoor-air damper position signal is at 100% (i.e., the outdoor-air damper is fully open). When the outdoor-air damper is fully open, the mixed-air temperature should be nearly equal to the outdoor-air temperature. However, in the case of AHU-2, the mixed-air temperature is greater than outdoor-air temperature by 2°F to 15°F. If the mixed-air and outdoor-air temperatures are nearly equal, they should be close to the solid line (say within ±2°F).

Another plot, mixed-air temperature as a function of the return-air temperature when the outdoor-air damper position signal is at its minimum position, is shown in Figure 25. Considering that the zone set-point temperatures are around 75°F, the return-air temperature appears to be in the acceptable range (73°F to 80°F). When the outdoor-air damper is at the minimum position and outdoor-air temperature is higher than return-air temperature, the mixed-air temperature should be greater than the return-air (i.e., above the solid line in Figure 25). Likewise, when the outdoor-air temperature is lower than return-air temperature, the mixed-air temperature should be lower than the return-air temperature (i.e., below the solid line in Figure 25). However, the mixed-air temperature is always higher than the return-air temperature (i.e., above the solid line). By comparing the results from Figure 24 and Figure 25, it appears that the mixed-air temperature sensor is probably faulty.

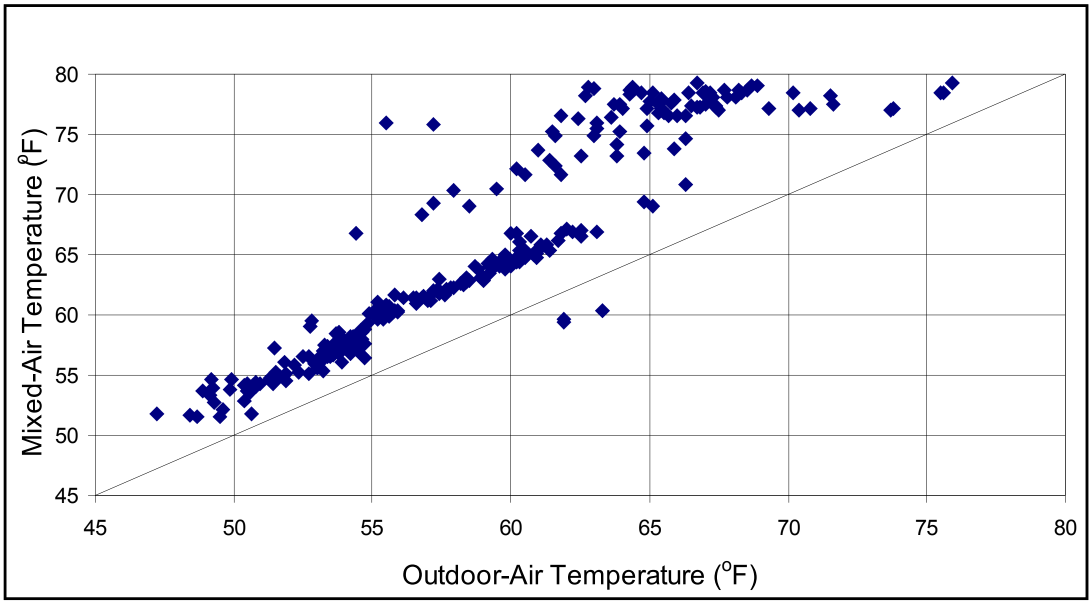


Figure 24 – Measured Values of Mixed-Air Temperature as a Function of Measured Outdoor-Air Temperature for AHU-2 when the Damper is Fully Open

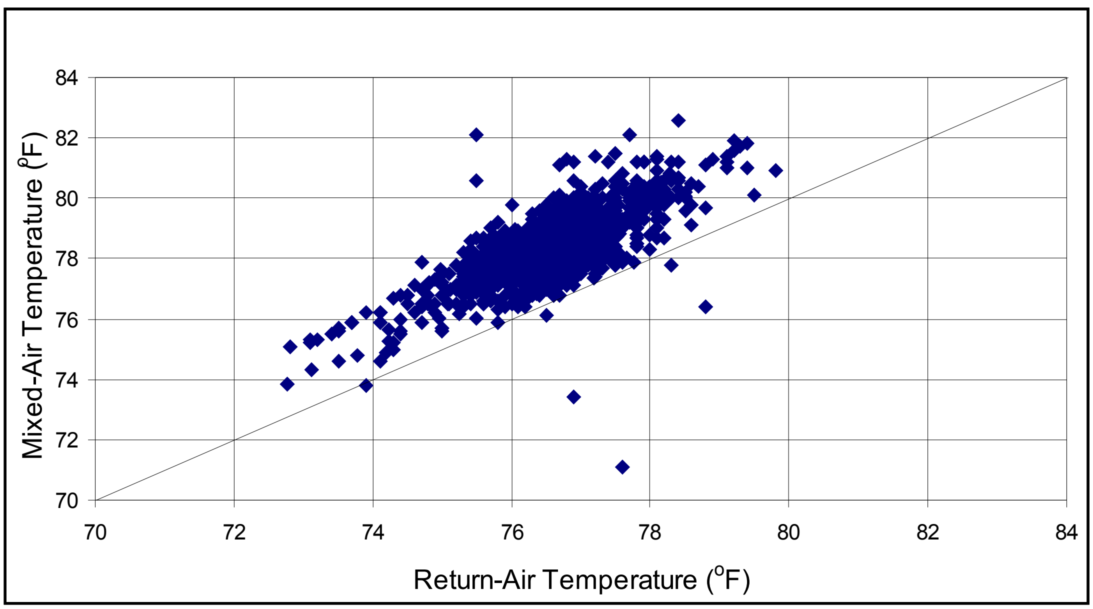


Figure 25 – Measured Values of Mixed-Air Temperature as a Function of Measured Values Return-Air Temperature for AHU-2 when the Damper is Fully Closed

At Symphony Towers there are two outdoor-air temperature sensors serving the four AHUs. AHU-1, AHU-2 and AHU-3 share the same outdoor-air temperature sensor, while AHU-4 has its own outdoor-air temperature sensor. As another check we can compare the values simultaneously indicated by the two outdoor-air temperature sensors. If they are both operating correctly, the values should be nearly equal[6] (Figure 26). Although for the most part, the values from the two outdoor-air temperature sensors are equal, there are major differences as well. So, this test is inconclusive.

Because the results from AHU-1 did not indicate any temperature-sensor problem, the outdoor-air temperature and mixed-air temperature from AHU-1 can be compared when the outdoor-air damper is fully open (Figure 27). The mixed-air temperature is nearly equal to the outdoor-air temperature, although there is a small bias with the mixed-air temperature slightly exceeding the outdoor-air temperature for outdoor-air temperatures below 55 °F and being slightly below it for outdoor-air temperatures above 60 °F. The difference in mixed-air and outdoor-air temperature measurements for AHU-1 is within the manufacturer specified accuracies for the two sensors. Therefore, it can be concluded that the outdoor-air temperature sensor being used for AHU-1 is good; as a result, the sensor for AHU-2 also is probably not faulty. The mixed-air temperature sensor for AHU-2 is probably faulty; however, site inspection is still required to confirm this diagnosis.

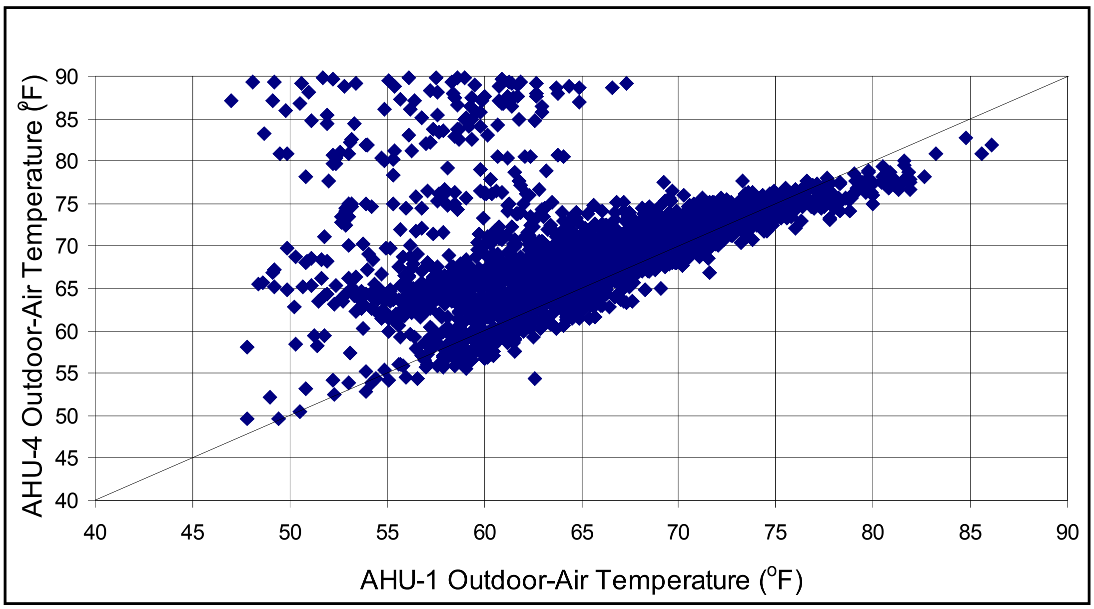


Figure 26 – Comparison of Measured Values of the Outdoor-Air-Temperature Sensors for AHU-1 and AHU-4

[6] This does not guarantee that the sensors are correct, only that they are consistent with one another; however, the two sensors being identically incorrect is improbable.

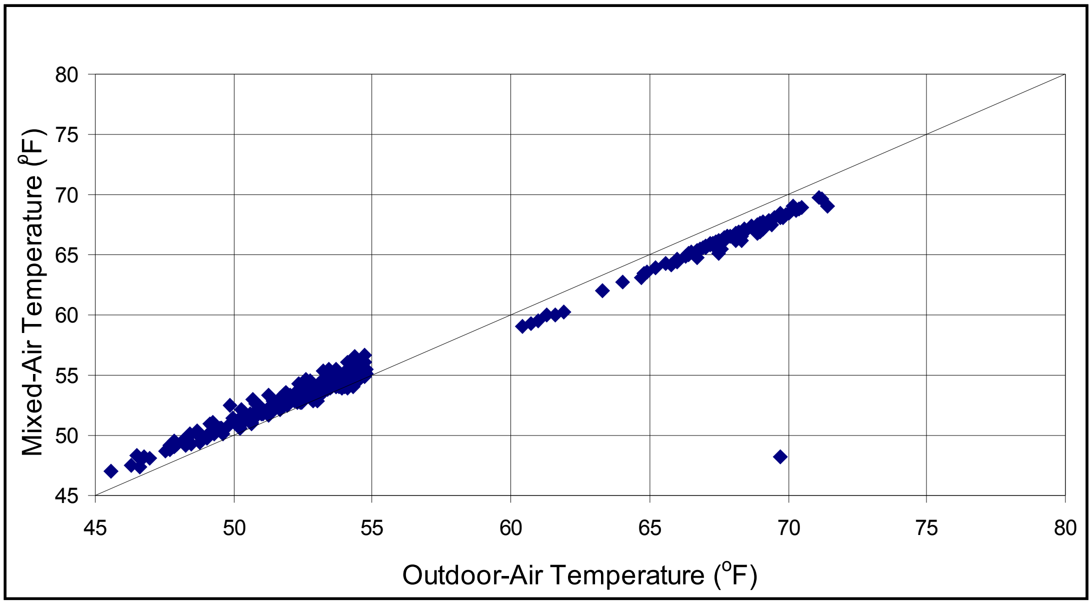


Figure 27 – Measured Values of Mixed-Air Temperature as a Function of Measured Values Outdoor-Air Temperature for AHU-1 when the Outdoor-Air Damper is Fully Open

8.5 Results for AHU-3

In April 2000, the WBD was set up to automatically collect and process data from AHU-3 though the end of the demonstration period. Like AHU-1 and AHU-2, there were several gaps in data from AHU-3, again, primarily as a result of manual termination of the data collection software on the operator's workstation.

The results from the WBD indicate that AHU-3, like AHU-1 and AHU-2, is being operated improperly. A screen shot of the processed results for the time period between June 1 and July 1, 2000, is shown in Figure 20Figure 28. A significant number of cells for occupied hours (6 a.m. to 9 p.m.) are yellow, followed in frequency by grey, blue and red. When there are a number of yellow and blue cells, in most cases, this indicates a problem with the temperature sensors (outdoor-air, return-air or mixed-air). Browsing a number of non-white and non-grey cells indicates a temperature-sensor problem in almost all cases.

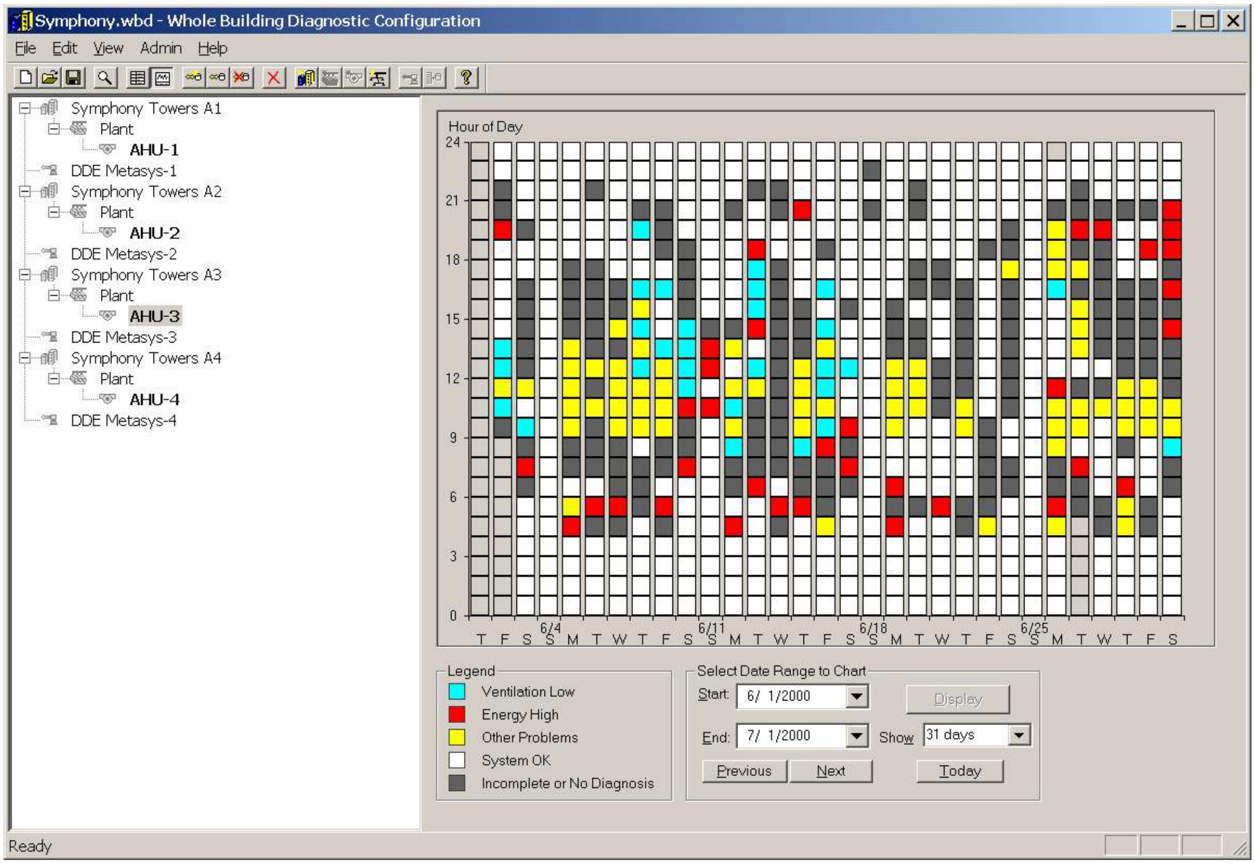


Figure 28 – WBD Diagnostic Results for AHU-3 for a Period from June 1 through July 1, 2000

The most current data (at the time of writing this report) is shown in Figure 29. The display appears similar to the one shown in Figure 28, although there are more red cells than any other non-white cells.

The frequency of problems (March 2001 and January 2003) reported for AHU-3 is shown in Table 7. The results indicate that AHU-3 operates about 10% of the occupied period with a control problem, 6% with inadequate ventilation, and 6% with low economizer flow (economizer not fully open). Although a temperature-sensor problem exists at all times, it only manifests itself about 30% of the time, during occupied hours.

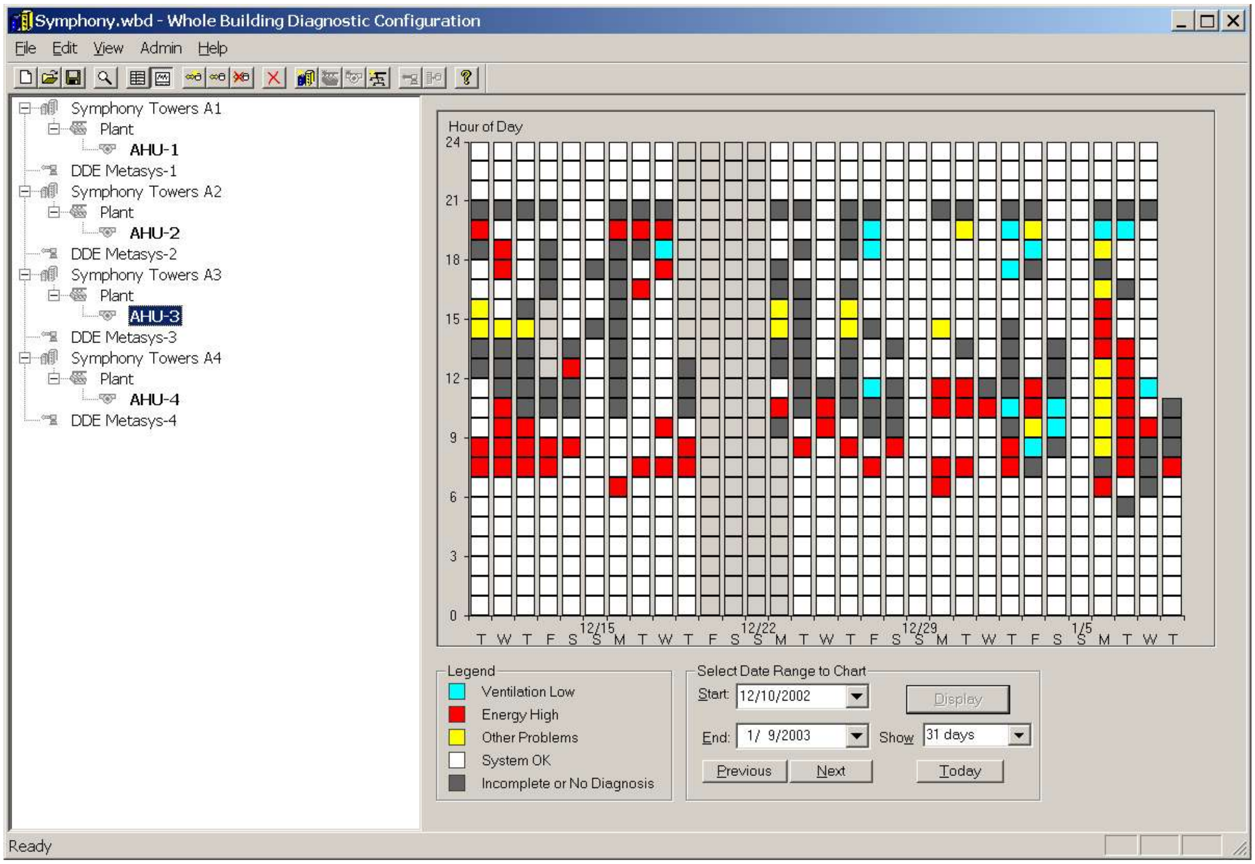


Figure 29 – WBD Diagnostic Results for AHU-3 for a Period from December 10, 2002, through January 9, 2003

Table 7 – Frequency of the Problems for AHU-3 when the Supply-Fan was Operating (March 2001 through January 2003)

Category of Operational States	Average Reliability Score	Number of Occurrences	Percent of Total Occupied Hours (%)
Control Problem	0.874	427	10.0
Control Problem - Excess Energy	0.948	99	2.3
Excess Ventilation	0.860	219	5.2
Low Economizer Flow	0.854	252	5.9
Inadequate Ventilation	0.869	263	6.2
OK but incomplete diagnosis	0.912	1,510	35.5
Operation OK	0.731	1,481	34.8
Total		**4,251**	**100**

8.6 Additional Analysis of Data from AHU-3

The OAE diagnostician identified a temperature-sensor problem but was unable to diagnose which of the three sensors was faulty. Additional analysis beyond the normal WBD analysis is presented in this section to provide insight into the cause of this problem. First, Figure 30 shows the plot of the measured mixed-air temperature as a function of the measured outdoor-air temperature when the outdoor-air damper position signal is at 100% (i.e., outdoor-air damper is fully open). When the outdoor-air damper is fully open, the mixed-air temperature should be nearly equal to the outdoor-air temperature. However, for AHU-3 the difference between the mixed-air temperature and outdoor-air temperature is about -2ºF to +7ºF. If the mixed-air and outdoor-air temperatures are nearly equal, the data points should all be close to the solid line (within ±2ºF). Although the difference between the outdoor-air and mixed-air temperature is not as large as it was with AHU-2, it is significantly greater than the accuracies specified by the manufacturer, so we can conclude that these two sensors don't adequately agree.

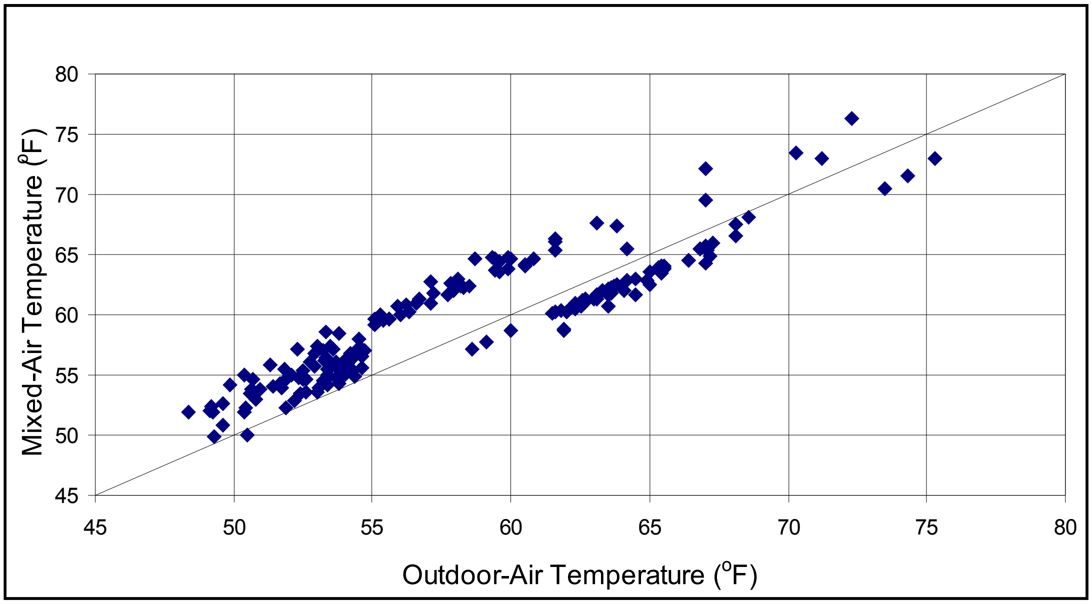


Figure 30 – Measured Values of Mixed-Air Temperature as a Function of Measured Values Outdoor-Air Temperature for AHU-3 when the Damper is Fully Open

Another plot of the mixed-air temperature as a function of the return-air temperature is shown in Figure 31. These data correspond to times when the outdoor-air damper position signal is at the minimum position (i.e., fully closed). Considering that the zone temperature set points are around 75ºF, the range of return-air temperatures appears to be acceptable (most between 71ºF and 75ºF). When the outdoor-air damper is in the minimum position and the outdoor-air temperature is higher than the return-air temperature, the mixed-air temperature should be slightly greater than the return-air temperature (or should be above the solid line). Likewise, when the outdoor-air temperature is lower than return-air temperature the mixed-air temperature should be lower than the return-air (or should be below the solid line). The mixed-air temperature does show such a pattern, i.e., above and below the solid line, but there are also several hours when that is not true.

The previous analysis of AHU-2 data concluded that the outdoor-air temperature sensor was fine. AHU-3 shares an outdoor-air temperature sensor with AHU-1 and AHU-2; therefore, we can assume that its outdoor-air temperature sensor is operating properly. The problem can then be isolated to a faulty mixed-air temperature sensor or to a difference between the actual outdoor-air temperature at the intake of AHU-3 and the outdoor-air temperature that is being sensed at AHU-1 (the outdoor-air temperature sensor is positioned close to AHU-1). Building staff should independently (possibly using a hand-held temperature measuring instrument) determine which of these problems exists.

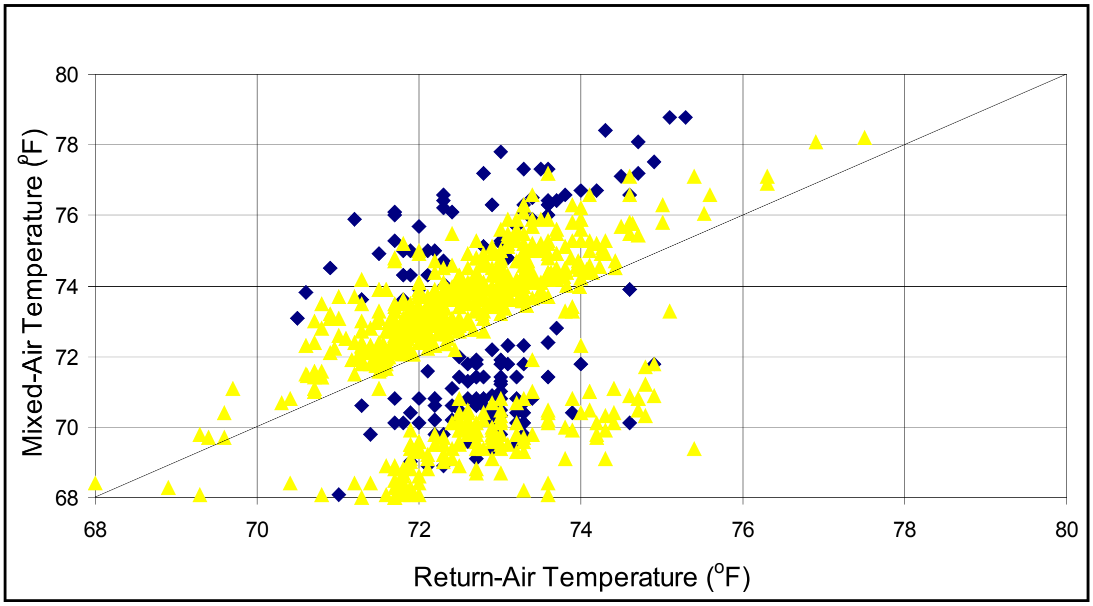


Figure 31 – Measured Values of Mixed-Air Temperature a Function of Measured Values Return-Air Temperature for AHU-3 when the Damper is Fully Closed (yellow marker represent conditions when outdoor-air temperature is greater than return-air temperature and blue marker represent conditions when outdoor-air temperature is less than return-air temperature)

8.7 Results for AHU-4

In April 2000, the WBD was set up to automatically collect and process data from AHU-4 though the end of the demonstration period. Like the other AHUs, there were several gaps in the data from AHU-4, again, primarily because of manual termination of the data collection software on the operator's workstation.

The results from the WBD indicate that AHU-4, like the other AHUs, is operating improperly. A screen shot of the processed results for the time period between December 11, 2001, and January 10, 2002, is shown in Figure 32. Almost all cells during occupied hours (6 a.m. to 9 p.m.) are yellow, with a few blue and grey cells. When there are a significant number of yellow and blue cells, this generally indicates a problem with the temperature sensors (outdoor-air, return-air or mixed-air). Browsing a number of yellow cells indicates a temperature-sensor problem in almost all cases.

The most current data (at the time of writing the report) is shown in Figure 33. The screen shot appears to be similar to that shown in Figure 32, although there are more red cells.

The frequency of problems (March 2001 and January 2003) reported for AHU-4 is shown in Table 8. The AHU-4 operates almost 26% of the occupied period with a control problem, 3% with inadequate ventilation, 3% excess ventilation and 3% with low economizer flow (economizer not fully open). Although the temperature-sensor problem exists at all times, it only manifests about 36% of the time, during the occupied hours. Based on this information, the building staff could investigate further, possible using a hand-held temperature instrument, to determine which of these three sensors is faulty.

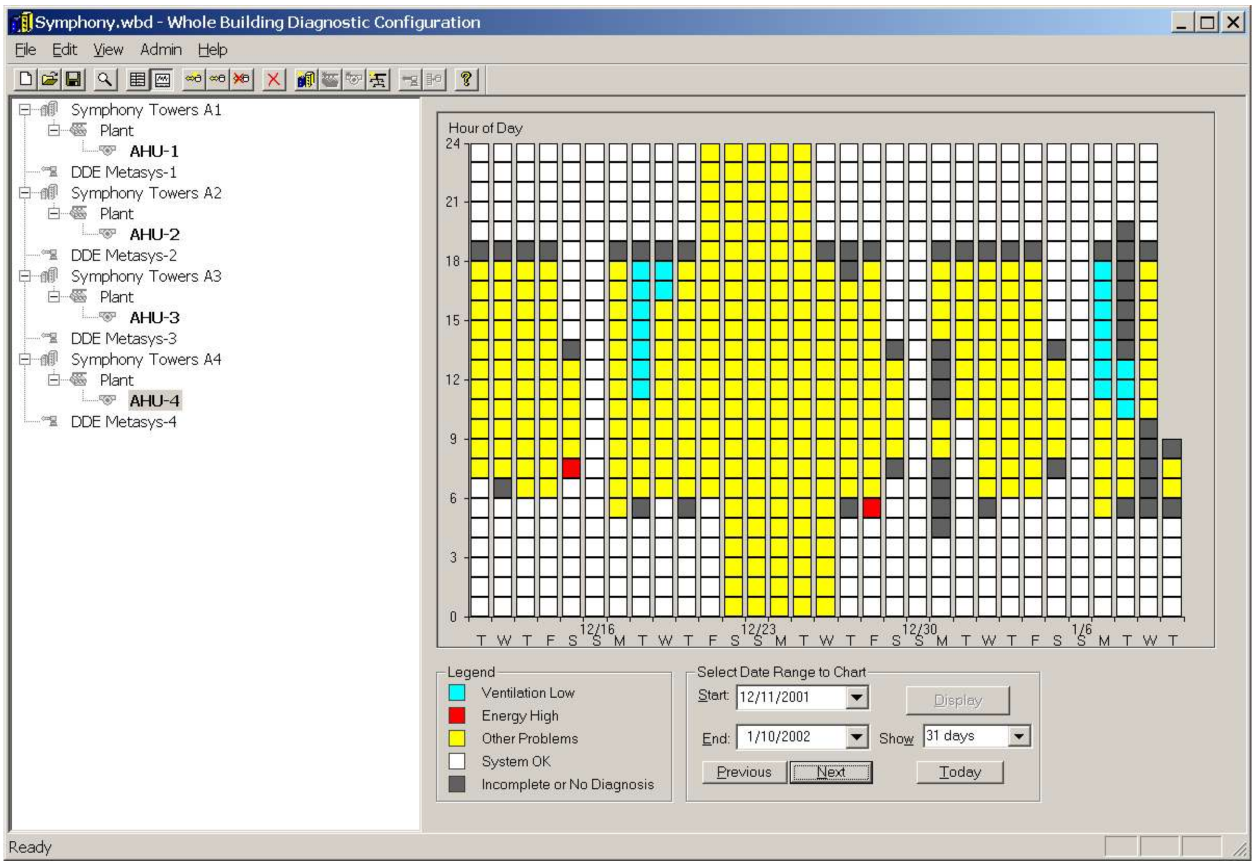


Figure 32 – WBD Diagnostic Results for AHU-4 for a Period from December 11, 2001, through January 10, 2002

8.8 Additional Analysis of Data from AHU-4

The OAE diagnostician identified a temperature-sensor problem but was unable to diagnose which of the three sensors was faulty. Additional analysis beyond the normal WBD analysis is presented in this section to provide further insight into the cause of this problem. Figure 34 shows the measured mixed-air temperature as a function of the measured outdoor-air temperature for conditions when the outdoor-air damper position signal is at 100% (i.e., outdoor-air damper is fully open). When the outdoor-air damper is fully open, the mixed-air temperature should be nearly equal to the outdoor-air temperature. For AHU-4, however, the mixed-air temperature is significantly lower than the outdoor-air temperature in most cases (up to 90ºF lower). In only a few cases is the measured mixed-air temperature greater than the measured outdoor-air temperature. It is clear from Figure 34 that the outdoor-air temperature measurement is faulty because it has values far greater than expected in the San Diego climate (as high as 140ºF).

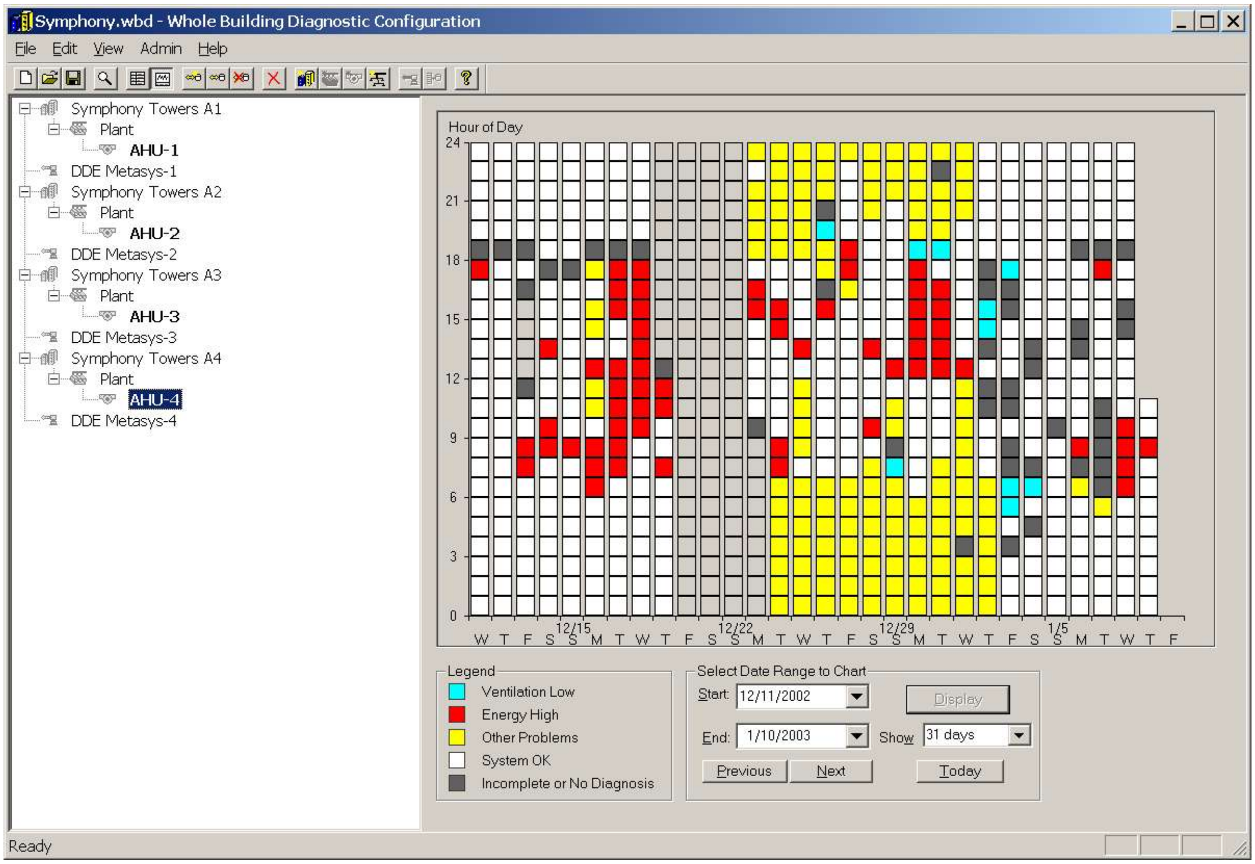


Figure 33 – WBD Diagnostic Results for AHU-4 for a Period from December 11, 2002, through January 10, 2003

Table 8 – Frequency of the Problems for AHU-4 when the Supply-Fan was Operating (March 2001 through January 2003)

Category of Operational States	Average Reliability Score	Number of Occurrences	Percent of Total Hours (%)
Control Problem	0.967	1,010	25.5
Control Problem - Excess Energy	0.954	3	0.1
Excess Ventilation	0.876	126	3.2
Low Economizer Flow	0.896	134	3.4
Inadequate Ventilation	0.877	133	3.4
OK but incomplete	0.888	1,115	28.1
Operation OK	0.748	1,447	36.5
Total		**3,968**	**100**

A plot showing the measured mixed-air temperature as a function of the measured return-air temperature is shown in Figure 35 for conditions when the outdoor-air damper position signal is at the minimum position. Considering that the zone temperature set point is around 75ºF, the return-air temperature appears to be in the acceptable range (a little less than 73ºF to little greater than 79ºF). When the outdoor-air damper is in the minimum position and the outdoor-air temperature is higher than the return-air temperature, the mixed-air temperature should be slightly greater than the return-air temperature (or should be above the solid line). Likewise, when the outdoor-air temperature is lower than return-air temperature, the mixed-air temperature should be lower than the return-air temperature (or should be below the solid line). The mixed-air temperature spans across the solid line and mostly follows the expected trend, but there are few hours when the trend does not hold.

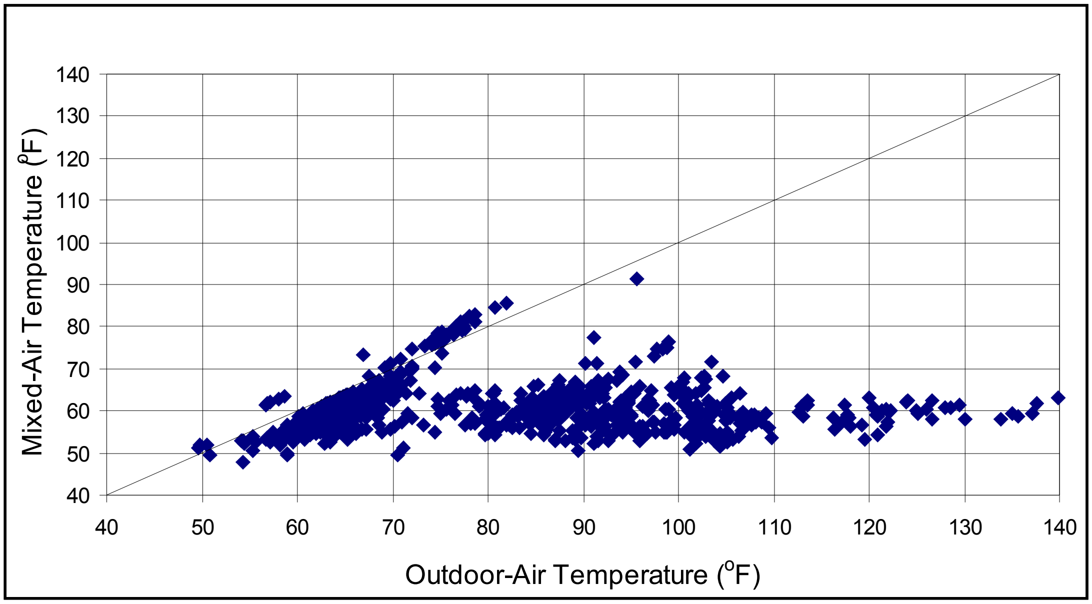


Figure 34 – Measured Values of Mixed-Air Temperature as a Function of Measured Values Outdoor-Air Temperature for AHU-4 when the Damper is Fully Open

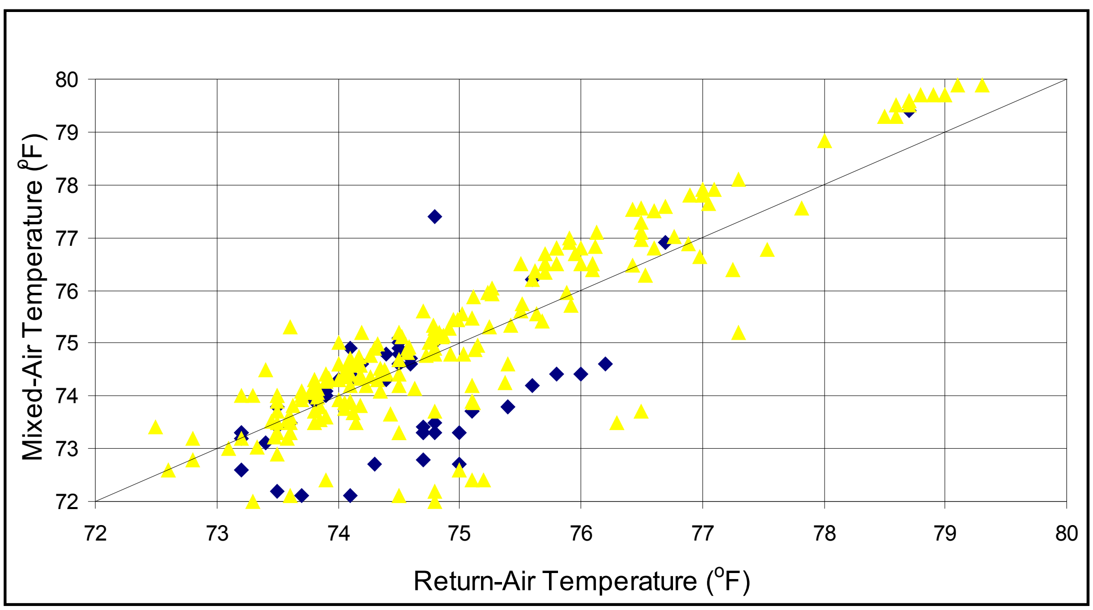


Figure 35 – Measured Values of Mixed-Air Temperature as a Function of Measured Values Return-Air Temperature for AHU-4 when the Damper is

Fully Closed (yellow marker represent conditions when outdoor-air temperature is greater than return-air temperature and blue marker represent conditions when outdoor-air temperature is less than return-air temperature)

9 Savings Opportunities for AHU-1

Correcting the energy-wasting problems identified by the OAE will produce reductions in energy consumption and savings on energy expenditures. In this section, we present the estimated savings from correcting the problem with AHU-1 identified by the OAE during on-line use of the WBD. For this air handler, the minimum outdoor-air damper setting was greater than the minimum required to provide adequate ventilation with outdoor air, and as a result energy was being wasted (see Sections 8.2).

The other three air-handling units (AHU-2, AHU-3, and AHU-4) were found to have faulty temperature sensors. Faulty readings from those sensors prevent us from estimating savings that would result from correcting those problems because we have no (reliable) data upon which to base estimates of savings. This also makes the energy and cost estimates provided by the OAE meaningless for those air handlers. Sensor problems present a quandary in this respect. If building staff do not correct or replace faulty sensors, control of the affected building systems will be wrong – the building equipment will not behave as desired – but the energy and cost impacts of the bad sensors cannot be determined because no good measured data are available upon which to base calculations of deviations from desired behavior. Therefore, the severity of the problems resulting for the bad sensors cannot be assessed. Building staff must decide whether they want to control their building or not. If the answer is affirmative, they replace the sensors; if not, the affected equipment continues to operate out of control in response to bad measurements from the failed sensors.

The savings associated with correcting the problem with AHU-1 were estimated using the simplified methodology described in Appendix A: Method for Estimating the Annual Energy Savings. The impact estimates are based on both the measured data and user-specified inputs [e.g., the system coefficient of performance (COP) and cost of energy]. Because measured values are used in estimating the impacts, the sensors must be fault free. If the AHU has a faulty sensor (especially, the outdoor-air, return-air or mixed-air temperature), the estimates are not accurate and cannot be relied upon. The sensors for AHU-1 were found to be good and, therefore, savings opportunities could be estimated. Major assumptions used in calculating the savings are shown in Table 9.

The estimated annual cooling energy savings from correcting the problem were 81,000 kWh with a corresponding value of about $12,200. The estimated energy and cost impacts are conservatively low because only the impacts on cooling energy were determined. The estimate does not impact heating energy. Heating is provided by reheat of the supply air before it enters the building spaces, and no information is currently collected by the WBD on terminal-box reheat. In addition, other operation problems may have been present for AHU-1, but the presence of the problem found may have masked these other problems. Before the *single-fault* nature of the logic implemented in the OAE, it only identified one prominent fault at a time (see Section 6.7). As a result, addition opportunities to improve the performance of AHU-1 may be available, as well as the associated savings. The OAE will reveal other problems after the one identified here is corrected.

Table 9 – Assumed and Calculated Values of Key Variables for Impact Estimates (see Appendix A for more information).

Coefficient of performance of the chilled water system (including chillers, pumps, cooling towers)	2.5
Marginal cost of electric energy including demand	0.15 $/kWh
Average return-air temperature	76ºF
Average return-air relative humidity	47%
Average speed of the supply air fan	80%
Supply air flow rate	80,000 cfm
Enthalpy dead-band	1.3 Btu/lb
Actual average minimum outdoor-air fraction	0.72
Desired minimum outdoor-air fraction	0.20

10 User Impressions of the WBD

An exit interview was conducted with Mr. Dishman, Energy Manager for Symphony Towers, in February 2003. The results of that interview are summarized in this section.

10.1 General

Mr. Dishman thought the WBD diagnostic tool set helped him in evaluating trends and identifying operational issues related to the four AHUs at Symphony Towers. In addition, he expressed that diagnostic tools such as WBD would help building mangers, operators, and owners by providing them with the ability to evaluate real-time data and perform corrective actions as required. He added that more diagnostics tools are needed that cover the entire HVAC systems spectrum. His staff currently spends almost 16 hours a week chasing problems.

10.2 OAE Interface and Diagnostics

On a scale of 1 to 5 (1 being very easy and 5 being very difficult to use) Mr. Dishman gave the WBD a rating of 2 on ease of use. This indicates that he found it somewhat easy to use. He indicated that the OAE tool was only relevant for building operators and not the building managers or owners. Although he did not actually configure any AHUs in the OAE diagnostician, his impression was that it is somewhat easy to configure. We, the investigators, are not sure what led him to this conclusion.

Mr. Dishman indicated that he often reviewed results and confirmed problems that the OAE reported by visually inspecting the AHUs. Despite this, none of the problems identified, with the exception of the one found during the off-line tests, were corrected. When asked about recommendations for changes or improvements to the OAE/WBD, Mr. Dishman indicated that the tools were fine and did not need any improvements. When asked if he would install additional sensors if that allowed for better diagnosis of problems, he indicated that he would. Because part of the WBD was run on an operator's workstation, we asked Mr. Dishman if that interfered with the operations, and he reported that he thought it did. He provided no detail regarding how the WBD might have interfered with operations.

Although the building operators were trained on how to view OAE results and interpret the information they provided, none of them actually reviewed the results during the demonstration. This may be a critical missing link in the process of using such tools, needs which further investigation in future applications.

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12 Conclusions and Recommendations

The WBD OAE module was shown to successfully identify a number of major problems with the air-handling units at Symphony Towers. These findings are consistent with other demonstrations of the WBD, where OAE found similar problems that should have been detected at the time of commissioning or periodic maintenance.

The OAE diagnostic module identified problems with all four AHUs at the Symphony Towers. Based on the results, we recommend a few corrective actions for the Symphony Towers air handlers:

- modify the minimum damper setting in the control system for AHU-1 to meet ASHRAE Standard 62 (ASHRAE 2001) levels; the current setting significantly exceeds the requirement of the standard and is costing the building over **$12,000** per year

- calibrate all temperature sensors for AHU-2, in particular the mixed-air temperature sensor, which might need replacement

- calibrate all temperature sensors for AHU-3, in particular the mixed-air temperature sensor, which may need replacement

- calibrate all temperature sensors for AHU-4, in particular the outdoor-air temperature sensor, which may need replacement

- consider reducing the minimum flow rate for all four AHUs. For all four AHUs, the flow rate does not modulate below 50%. Reducing the flow would save cooling/heating energy and fan energy, and correspondingly reduce costs. This was not detected by the OAE, but was found while performing additional analysis off-line.

Observations by users at the building provided mixed results. Although more knowledgeable and experienced users of the WBD were comfortable with the design of the module's user interface and diagnostics, they both proved to make the results difficult for inexperienced users to interpret when several problems occurred simultaneously. This may have implications for interface design changes in the future. For example, a simpler user interface that produces an action item list or list of problems based on OAE results for a block of time may be preferable to users overwhelmed by the detailed hourly results.

Installation of the WBD and collection of data from the air handlers were smooth at this site. The OAE data-collection module has been extensively tested at other field sites with similar control systems, so no significant problems were encountered with the installation at Symphony Towers. The automated processing of the data proceeded very well for all four air handlers, with little or no attention paid to it. However, there were large gaps in the data collected mainly caused by manual shutdown of the data acquisition module on the operator's workstation.

The demonstration reinforced the notion that diagnostic tools produce savings only when the identified problems are fixed. Merely identifying operation problems and their impacts is not sufficient by itself; building staff must fix them. If building staff are not able to use their control systems to correct problems, are too busy with other duties, or lack resources to obtain help from contractors, savings will not be realized. A delivery mechanism is needed that helps ensure that building staff take action when alerted to problems with significant impacts.

The time and cost of diagnostic-tool installation is a significant component to implementing diagnostic technologies. Labor costs to set up tools like the WBD (~1 week) will likely exceed the purchase cost of commercialized software. Sites with larger air handlers (10,000 cfm or larger air flow rates) have greater savings per problem fixed, while installation costs do not vary with air handler size (i.e., savings are greater relative to costs). Installation costs per air-handler also go down as the number of air handlers at a site increases, provided the units use similar operating control strategies and are part of the same underlying control system.

Overall, the WBD OAE diagnostician was successfully applied at Symphony Towers. It identified problems with significant energy and cost penalties that would provide significant savings if fixed. Getting building staff to correct these problems, however, was difficult. This points to a need to develop a mechanism for delivering the OAE or providing its results to users in a way that better encourages them to correct the problems found.

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Appendix A
Method for Estimating the Annual Energy Savings

14 Appendix A: Method for Estimating the Annual Energy Savings

A simplified method that was used to estimate the cooling energy savings for AHU-1 is described in this appendix. The savings are estimated based on average weather for San Diego, California, as provided by a Typical Meteorological Year (TMY).[7]

The steps to estimate the cooling energy savings are:

1. Extract data for outdoor-air temperature and humidity for each hour of the TMY for San Diego. These data are used to represent outdoor conditions over the 12-month period for which savings are estimated.

2. Values of the return-air temperature and humidity were collected over the time period that the OAE diagnostician was used. Rather than accounting for variations in the conditions hourly over the course of a year, annual averages of the hourly values for times when the building was occupied were used in estimating savings. This was reasonable because return-air conditions did not vary substantially during occupied times. These average values along with values for other key input and calculated variables are shown in Table 9.

3. Several other variables needed to estimated energy savings and savings on energy expenditures were estimated and are shown in Table 9. These included:

    - Marginal cost of electricity (P_{elec}), given as an equivalent blended rate that includes both the consumption charge and demand charge

    - Full-load supply-air volumetric flow rate (v_{rated}), estimated as the rated air-flow rate of this air-handling unit

    - Average fan speed expressed as a fraction of full speed (fan $speed_{average}$), which for Symphony Towers is actually measured for use as an indicator of fan status, so an actual average value was determined

    - Enthalpy dead-band, obtained from the economizer control code

    - Coefficient of performance of the chiller system (COP), which was assumed equal to that of a typical chiller system, including energy use by all system components

    - Desired minimum outdoor-air fraction ($OAF_{desired\ minimum}$), which is the outdoor-air fraction corresponding to the damper position that provides the minimum outside air flow necessary to meet outdoor-air ventilation requirements. For constant volume systems or for estimates made using average flow rates, this OAF can be assumed constant.

[7] TMY weather data can be obtained from National Renewable Energy Laboratory website at the following url: http://rredc.nrel.gov/solar/old_data/nsrdb/tmy2/

4. Determine the times (hours) during which conditions are not favorable for economizing by comparing the outdoor-air enthalpy, determined from temperature and humidity data in the weather file, with the average return-air enthalpy. These are the hours when the outdoor-air damper should be at its minimum position. Conditions are not favorable for economizing when the difference between the return-air enthalpy ($h_{return\text{-}air}$) and outdoor-air enthalpy ($h_{outdoor\text{-}air}$) is greater than the enthalpy dead-band (1.3 Btu/lb), i.e.,

$$(h_{return\text{-}air} - h_{outdoor\text{-}air}) > 1.3 \text{ Btu/lbm}$$

5. Calculate the actual average minimum outdoor-air fraction ($OAF_{actual\ avg\ minimum}$) from data for the outdoor-air, return-air and mixed-air temperatures at times that the outdoor-air damper should have been at its minimum position (i.e., while not economizing), using the relation

$$OAF_{actual\,average\,minimum} = \frac{\displaystyle\sum_{\substack{i-hours\,unfavorable \\ for\ economizing}} \frac{\left(T_{mixed-air} - T_{return-air}\right)_i}{\left(T_{outdoor-air} - T_{return-air}\right)_i}}{N}$$

where T represents temperature, and N is the total number of hours unfavorable to economizing.

6. Compute the desired mixed-air enthalpy ($h_{mixed\text{-}air,\ desired\ min}$) for each hour when the conditions are not favorable for economizing. The desired enthalpy is obtained when the outdoor-air damper is at its desired minimum position. The desired minimum damper position is the damper position that provides just enough outdoor air to satisfy outdoor-air ventilation requirements. For constant flow systems, that position corresponds to a desired minimum outdoor-air fraction (OAF). As a result, the desired mixed-air enthalpy can be estimated using the relation

$$h_{mixed-air,\,desired\,minimum} = OAF_{desired\,minimum} \times h_{outdoor-air} + \left(1 - OAF_{desired\,minimum}\right) \times h_{return-air}$$

where h represents enthalpy.

7. Compute the mixed-air enthalpy for all times (hours) when the outdoor-air damper should be at its minimum position, i.e., the actual mixed-air enthalpy ($h_{mixed\text{-}air,\ actual\ minimum}$) for hours when the conditions are not favorable for economizing, which is given by

$$h_{mixed-air,\,actual\,minimum} = OAF_{actual\,minimum} \times h_{outdoor-air} + \left(1 - OAF_{actual\,minimum}\right) \times h_{return-air}$$

8. Compute the difference between item 7 and item 6 at each hour. This is annual enthalpy difference between actual and desired. The cooling energy impacts can be computed as

follows (average supply-air flow is computed as a product of full-load supply-air flow and average fan speed over the measured period):

$$Annual\ energy\ savings = \left[\frac{\left(V_{rated} \times fan\ speed_{average} \times \rho_{air} \frac{60\ \min}{hr} \right)}{\frac{3414\ Btu}{kWh} \times COP} \right]$$
$$\times \sum_{\substack{i=hours\ unfavorable\ for \\ economizing}} \left(h_{mixed-air,\ actual\ \minimum} - h_{mixed-air,\ desired\ \minimum} \right)$$

where the annual energy savings are in kWh/year, the rated volumetric flow rate (v_{rated}) is in cubic feet per minute, the average fan speed (fan $speed_{average}$) is a dimensionless fraction of the full rated speed, ρ_{air} is the average density of air in lbm/ft^3, and the values of enthalpy are in Btu/lbm.

9. Compute the annual savings on energy expenditures using the relation

Annual Cost Savings = Annual Energy Savings x P_{elec}.

The annual energy and cost savings from correcting the problem with AHU-1 in Symphony Towers are also equal to the annual energy penalty and extra cost if the problem is not fixed.

Task Report for the

Energy Efficient and Affordable Small Commercial and Residential Buildings Research Program

a Public Interest Energy Research Program sponsored by the California Energy Commission

Project 2.4 – Demonstration of the Whole-Building Diagnostician

Task 2.4.10 – Multi-Building Operator Demonstration – On-line Test

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1 Executive Summary

This report on Task 2.4.10 – Online Test for the Multi-Building Operator Demonstration for Project 2.4 – Demonstration of the Whole-Building Diagnostician, documents the online analysis of data for the multi-building operator demonstration being conducted at Alameda County buildings. Battelle working with Newport Design Consultants implemented the online test configuration, data collection, data analysis, and documentation for this demonstration.

The online test was designed to evaluate the Outdoor-Air Economizer (OAE) diagnostic module's capabilities to automatically and continually diagnose operational problems with air-handling units (AHU's). As part of this online demonstration, two AHU's at the Hayward Hall of Justice (HHOJ), two AHU's at the Alameda County Courthouse (OPMC), three AHU's at the Office of Emergency Services (OES) and one AHU at the Emergency Operation Center (EOC) were monitored. The measured data that were collected on a continuous basis included: 1) outdoor-air temperature, 2) return-air temperature, 3) mixed-air temperature, 4) supply-air temperature, 5) chilled water valve position, 6) supply-fan status, 7) outdoor-air relative humidity, 8) return-air relative humidity 9) hot water valve position 10) supply air setpoint 11) mixed-air setpoint and 12) economizer damper position.

The air handler's control strategy for the outdoor-air and economizer, and the schedule (times of day and days of week) for which the minimum outdoor air must be supplied for the occupants was entered into the WBD's configuration for the air handler. This information was largely obtained from Alameda County GSA Technical Services Department; some items were ascertained by observation of the raw data delivered, as is typical in most WBD installations.

For online tests, the data from AHU's was automatically collected using trend log data and logged into the diagnostician's database using a data collection module, which is also part of the Whole Building Diagnostician (WBD). Although the data requests can be made at any frequency, at Alameda County, the data was requested at 5-minute intervals and integrated over the hour before being processed by the OAE diagnostic module. The online data collection process started in February of 2001 at the OPMC AHU's and November of 2002 at the HHOJ AHU's. The three packaged AHU's at the OES building were dropped from the on-line analysis because they did not have all the necessary data points to perform the diagnostics. Because the units were packaged direct-expansion units, the heating and cooling modes were not directly accessible through the building automation system. The AHU's at the EOC building lacked return-air temperature, which is a critical input required for diagnostics; therefore, it was dropped as well. Due to a number of problems with the data collection, a number of gaps in the data were encountered.

All four AHU's at Alameda County had outstanding problems. The predominant problem for each of the four AHU's with corresponding energy cost impact for the demonstration period are: 1) HHOJ AHU S-1 had the damper not fully opening during economizer operations with an energy cost impact $1,800, 2) HHOJ AHU S-2 had the damper not fully opening during economizer operations with an energy cost impact $300, 3) OPMC AHU S-1 had the damper not fully opening during economizer operations with an energy cost impact $15,750 and 4) OPMC

AHU S-2 had the damper not fully opening during economizer operations with an energy cost impact $10,000.

Mr. Lucas, Energy Project Manager for Alameda County, indicated that the WBD tool set was useful and added that he would like more diagnostic tools such as WBD for other HVAC systems. Mr. Lucas indicated that the user interface for both the WBD and the OAE diagnostician where easy to use with the exception of data collection. Although the OAE diagnostician has identified a number of problems, the site administrator and operators addressed only one problem.

The OAE diagnostician was shown to successfully identify problems with all four AHU's at Alameda County. These findings are consistent with the other field demonstrations of the WBD where OAE found similar problems that should have been detected at the time of commissioning. The demonstration showed that diagnostic technology is only as good as the fixes to the problems it identifies. That is, it is insufficient to merely identify problems and their impacts and expect operators will fix them as a result. If users are not proficient in using their control systems to correct problems, are too busy with other duties, or lack resources to obtain help from contractors, diagnostic technologies alone will not result in system efficiency improvements. Improvements can only be realized in buildings where identified problems are corrected. Future demonstrations or broad deployment of the WBD must include a mechanism for ensuring identified problems get fixed. This could come from within an agency or be provided as part of the deployment, but appears necessary if diagnostics are to do more than simply identify problems and actually proceed to deliver energy savings.

2 Purpose of This Task Report

In April 2000, the California Energy Commission (Commission) initiated a project to evaluate a DOE-developed technology, the Whole-Building Diagnostician (WBD), for automatically and continually diagnosing operational problems in buildings. The Whole-Building Diagnostician is a pre-commercial, production-prototype software package that connects to digital control systems (e.g. energy management systems), utilizing data from the control system's sensors to analyze overall building and system performance. It currently consists of two diagnostic tools, or modules, with a user interface designed to readily identify problems and provide potential solutions to building operators. The Outdoor-Air/Economizer module (OAE), the subject of this demonstration, diagnoses whether each air handler in a building is supplying adequate outdoor air for the occupants it is designed to serve, by time of day and day of week. It also determines whether the economizer is providing free cooling with outside air when appropriate and not wasting energy by supplying excess outside air. In addition to the two diagnostic modules, the WBD also has a data module to automatically retrieve data from some building automation systems.

This report documents the results of **Task 2.4.10 – On-line Test for the Multi-Building Operator Demonstration for Project 2.4 – Demonstration of the Whole-Building Diagnostician.** The multiple-building operator demonstration was conducted at two of Alameda County facilities in the cities of Oakland, San Leandro and Hayward. Some characteristics of the buildings are listed in the next section.

This project is intended to demonstrate the WBD's current automated diagnostic tools in three contexts:

- **Single-Building Operator Demonstration –** use of the WBD by dedicated operators for a single, Class A office building
- **Multi-Building Operator Demonstration –** use of the WBD by a set of supervisory operators for a set of commonly managed and operated buildings that share a control system infrastructure
- **Service Provider Demonstration –** use of the WBD by third-party analysts of a service company providing contracted retrofit and O&M services to buildings and facilities.

In each of these three contexts, Project 2.4 is designed to test and demonstrate automated diagnostics using the Whole-Building Diagnostician (WBD) in actual buildings with actual operators and energy service providers to:

- Prove their efficacy in automatically detecting energy efficiency and outdoor-air supply problems in buildings
- Test and demonstrate the ability of users to interpret and act upon the information provided by the tools to correct building operational problems
- Develop case studies of the impacts of using the tools in terms of the type and number of problems found, the energy savings and fresh air supply impacts of correcting the problems, and
- Provide early feedback from users, based on their experiences with actual automated diagnostic tools, to guide development and implementation of other tools in the future, including those in the program plan.

This report focuses on the on-line test results for the Multi-building operator demonstration and is a follow up to an earlier report that described the off-line test results for the same site. This demonstration, which is the second demonstration, is intended to test the ability of a multi-building operator to use and interpret the results from the WBD tool. The first demonstration was to test the WBD tool in a single-building with a single operator. The second demonstration was to test the WBD in a multi-building, multi-operator environment. The results from the first demonstration is reported in a companion report.

After the demonstration site was selected, the demonstrations began with an off-line test of the WBD's Outdoor-Air Economizer (OAE) diagnostic module. The off-line test was designed to determine the basic suitability of the demonstration site for testing the WBD. The three major criteria to determine the suitability were: accessibility of the control system sensors for data collection, whether the necessary sensors were present and reasonably accurate, and whether the OAE module could diagnose the control strategy for the air handlers' outdoor-air economizer systems. Off-line testing of the OAE module at Alameda County was successful because all three major criteria were satisfied.

The results of the on-line demonstration are presented in this report. In the section following this, the need for diagnostics in building systems is briefly discussed, followed by a section on basic information about what the WBD is, how it works, and a detailed description and capabilities of the OAE module. The Alameda County buildings are described next. Technical discussions including installation of the WBD, training of the Alameda County staff, the WBD's operation, problems identified by the OAE, potential savings from correcting the problems found, and issues that surfaced that have implications for facilities that might wish to use the WBD are also presented.

3 Alameda County Buildings

The multiple-building operator demonstration took place at the County of Alameda GSA Tech Services County Offices facilities using the buildings listed in Table 1.

The County of Alameda currently owns or leases approximately 120 buildings consisting of 6.2 million square feet of owned office space and 1.1 million square feet of leased office space. Among those buildings are a jail, a number of courthouses, clinics, office buildings and juvenile halls. Our demonstration sites, listed in Table 1, consist of 2 courthouses and 2 emergency buildings. These buildings were selected for the following reasons:

- ✓ They are the most important buildings to Alameda County
- ✓ They have been upgraded to the latest Control Systems International (CSI) control system
- ✓ They have central data archives
- ✓ They are suitable for the OAE diagnostician because they have mostly relatively large air-handlers servicing the buildings.

Table 1 – Alameda County Buildings in the Demonstration

Building	**Air-Handling Units (AHU's)**	**Square Footage**
Alameda County Courthouse / Wiley W. Manuel Courthouse (OPMC)	2	210,400
Hayward Hall of Justice (HHOJ)	2	191,300
Office of Emergency Services (OES)	3 – packaged	14,200
Emergency Operations Center (EOC)	1	20,000

The building's HVAC (heating, ventilating and air-conditioning) consists of hydronic systems with centrifugal chillers, and natural gas hydronic boilers. Four large variable-air-volume (VAV) air handlers with heating and cooling coils, differential dry-bulb controlled economizers and variable speed drives (see Table 1), serve the occupied space. A direct digital control (DDC) system from CSI controls the HVAC systems, which also provides a mechanism for trend logs.

Table 2 – Alameda County Air Handlers in the Demonstration

Air-Handler	Rated Flow (ft^3/min)
HHOJ AHUS-1	90,500
HHOJ AHU S-2	98,750
OPMC AHU S-1	103,750
OPMC AHU S-2	87,160

Note: Air handler rated flow is the design rating

The contact at Alameda County is Matt Muniz, Energy Program Manager and Don Lucas, Energy Project Manager. Don Lucas was designated as the primary administrator of the WBD at the site. (The Administrator has the highest-level permissions to change the configuration of the WBD to reflect changes to controls, add diagnosticians, rename buildings and components, reprocess data, etc.)

4 The Need for Diagnostics in Building Systems

Automated commissioning and diagnostic technologies are designed to ensure the ongoing performance of buildings at the highest possible levels of efficiency. Evidence of extensive performance problems in buildings shows that an efficient building stock will not result from solely designing efficient buildings and installing efficient equipment in them (Lunneberg 1999; also check the commissioning resources at http://www.peci.org).

These performance problems are not inherent with efficiency technologies themselves, but instead result from errors in installation and operation of complex building heating/cooling systems and their controls. It is also significant that these systems are becoming increasingly more sophisticated to obtain ever-higher levels of energy efficiency, adding to the complexity and subtlety of problems that reduce the net efficiency acquired. Such problems are even more common in existing buildings because they arise over time from operational changes and lack of maintenance (Claridge et al. 2000; also check the commissioning resources at http://www.peci.org). They often result in problems with comfort control and indoor-air quality that affect occupant health and productivity (Daisey and Angell 1998).

Assuring efficient performance by commissioning of new buildings followed by regularly scheduled preventative maintenance is clearly insufficient to address this issue. Manually commissioning[1] of buildings is valuable in terms of both finding problems and developing the techniques for doing so, but it is expensive. With only 1 to 2% of total construction costs devoted to commissioning (see the commissioning resources at http://www.peci.org) and the few experts available to provide such services in high demand, commissioning is not done adequately for most commercial buildings. Commissioning is difficult to sell in a low-bid construction environment, where variations in the effort allocated to commissioning can be the difference between winning and losing bids and where building owners (rightfully) feel they should not have to pay extra to get buildings to work properly. Further, commissioning is often short-changed because it largely occurs at the end of the construction process, when time-to-occupancy is critical and cost overruns drive last minute budget cuts in remaining items.

Effective, on-going maintenance of building systems as usually performed is notably ineffective, being almost exclusively complaint-driven and “quick fix” oriented. This is especially true for problems affecting air quality and efficiency because they are “silent killers” that go unnoticed until complete system failure occurs.

By embedding the expertise required to detect and diagnose operation problems in software tools that leverage existing sensors and control systems, detection and diagnosis can be conducted automatically and comprehensively without the ongoing cost of expensive human expertise. Further, this oversight remains as a legacy in buildings after they are constructed, protecting the

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[1] Commissioning is the process of systematically putting a building “through its paces,” checking that it performs as expected in terms of sensor and actuator connectivity and calibration, system modes, control sequences, and equipment capacities and conversion efficiencies. The term derives from the traditional acceptance process for naval ships, which must undergo a shakedown cruise to prove their speed, range, stability, maneuverability, communications, etc., to meet design specifications before they are accepted into service.

building systems against slow mechanical degradation, as well as faults inadvertently introduced by operators seeking to resolve complaints without finding root causes. The principal technical challenges are the construction of diagnostic techniques that 1) can be automated, 2) comprehensively diagnose the range and diversity of building systems and equipment, 3) make use of a minimal set of additional sensors beyond those used for control, and 4) are applicable for building commissioning, as well as ongoing diagnostics.

Currently, most building owners are not aware of the power of automated commissioning and diagnostic technology to provide them more cost effective, comfortable, and productive buildings. The technology is in its infancy and not yet well known in practice. Finally, energy service companies who may eventually offer commissioning and diagnostic services are slow to expand their business practices beyond their current focus on lighting and cooling equipment retrofits. Despite this current state, automated diagnostic technology offers promised a future with improved facility operation, better indoor environments, and enhanced and higher-quality offerings by service companies.

5 Background on the WBD

Developed by the Pacific Northwest National Laboratory (PNNL)[2] under funding from the Office of Energy Efficiency and Renewable Energy of the U.S. Department of Energy, with Honeywell, Inc. and the University of Colorado as subcontractors, the Whole-Building Diagnostician (WBD) is a production-prototype software package with two modules providing automated diagnostics for buildings based on data collected by direct-digital control (DDC) systems. These tools are deployed in the WBD's user interface and data and process management infrastructure.

The WBD's Outdoor-Air Economizer module diagnoses whether each air handler in a building is supplying adequate outdoor air for the occupants it is designed to serve, by time of day and day of week. It also determines whether the economizer is providing free cooling with outdoor air when appropriate, and is not wasting energy by supplying excess outdoor air. Few, if any, sensors other than those used to control most economizers are required, making the OAE practical in near-term markets because of its low cost. Early experience with the OAE in new and existing buildings in Washington and California has confirmed the broadly held suspicion that problems with outdoor-air ventilation control and economizing are endemic. The OAE has discovered problems in all but 1 of the roughly 35 air handlers examined to date, in existing and newly commissioned buildings.

The WBD also contains a Whole-Building Efficiency module that monitors whole-building and major subsystem (end-use) performance. It does this by tracking actual energy consumption and comparing it to estimated expected consumption as a function of time of day, day of week, and weather conditions. Using these data, it automatically constructs a model based on actual past system performance for a baseline period, and then alerts the user when performance is no longer as good as or, in the case of retrofits or operations and maintenance (O&M) programs, is better than past performance. The tool bootstraps itself to provide feedback during the initial training period after a period of about 4 to 6 weeks. Electricity or gas consumption sensors typically must be connected to the building's direct digital control (DDC) system to obtain the consumption data. This, however, is not an absolute requirement.

Both modules provide information to users in simple, graphical displays that indicate the presence or absence of problems at a glance. They also provide cost estimates of detected energy waste to provide feedback to users on the relative importance of the problems detected. These tools are available for commercialization through special use licenses from Battelle. The WBD's infrastructure is an open-protocol, public-domain framework designed to support the ready incorporation of new diagnostic tools from other developers in the future.

5.1 The WBD Infrastructure

The WBD currently consists of four primary modules: the two diagnostic modules, the user interface, and a database that stores measured data, as well as diagnostic results. These are connected by an infrastructure that provides data transfer, data management, and process control, as shown in Figure 1. Boxes represent major components; lines represent flows of data. Data is

[2] Operated for the U.S. Department of Energy by Battelle Memorial Institute under Contract DE-AC06-76RL01830.

automatically obtained at a user-specified sub-hourly frequency and averaged to create hourly values. As new hourly values become available in the database, the diagnostic modules automatically process them and produce diagnostic results that are also placed in the database. The user can then open the WBD user interface at any time to see the latest diagnostic results, and can also browse historical results.

Raw data (e.g., sensor measurements) may be obtained from a variety of data sources: a data logger or building management system, another database, or some other analytic software tool. The system also requires one-time entry of setup data that customizes the WBD modules to each specific building and heating/cooling/ventilation system. The system is written in the C++ language and uses an SQL database. The term DDE in Figure 1 refers to Microsoft's Dynamic Data Exchange protocol.

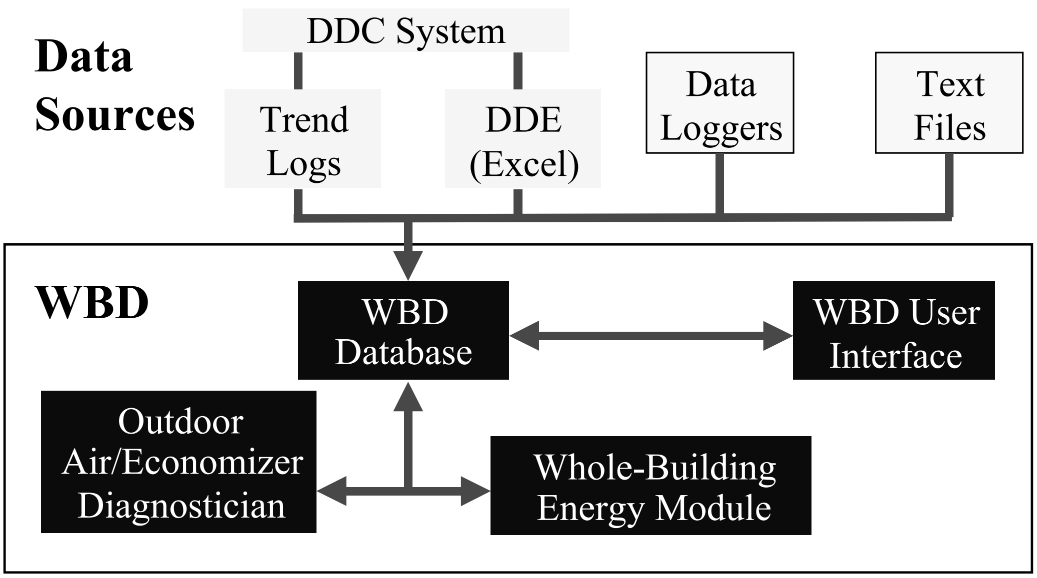

Figure 1 – Schematic Diagram of the WBD Software

6 The Outside-Air Economizer (OAE) Diagnostic Module

This section provides a brief overview of the Outside-Air Economizer (OAE) module. Additional information about the WBD and the OAE can be found in Brambley et al. (1998) and Katipamula et al. (1999). The OAE continuously monitors the performance of air handlers and can detect basic operation problems or faults with outside-air control and economizer operation. The current version detects about 25 different basic operation problems and over 100 variations of them [for details refer to Brambley et al. (1998) or Katipamula et al. (1999)]. It uses color-coding to alert the building operator when problems occur and then provides assistance in identifying the causes of problems and advice for correcting them. It, however, does not detect problems with the waterside or the refrigerant side of the air handler; it only detects problems on the airside, i.e., economizer operation and ventilation. If the air handler does not have an economizer, the OAE module can still detect problems with the outdoor-air ventilation.

6.1 Types of Economizer Controls Supported

The OAE module can diagnose abnormal operations or problems with several different types of economizer controls including: differential dry-bulb temperature-based, differential enthalpy-based, high-limit dry-bulb temperature-based and high-limit enthalpy-based.

With differential control strategies, the outside-air condition is compared with the return-air condition. As long as the outside-air condition is more favorable (for example, with dry-bulb temperature control, the outside-air dry-bulb temperature is less than the return-air temperature), outside air is used to meet all or part of the cooling demand. If the outside air alone cannot satisfy the cooling demand, mechanical cooling is used to provide the remainder of the cooling load.

With high-limit control strategies, the outside-air condition is compared to a single or fixed set point (usually referred to as a high limit). If the outside-air condition is below the set point, outside air is used to meet all or part of the cooling demand. Mechanical cooling provides any remaining cooling load.

In addition to these economizer control strategies, the OAE supports fault detection with both integrated and nonintegrated economizers. An integrated economizer, as its name implies, is fully integrated with the mechanical cooling system such that it can either provide all of the building's cooling requirements if outdoor conditions allow, or it can supplement the mechanical cooling when outdoor conditions are not sufficiently favorable to handle the entire cooling load. An economizer often has the ability to throttle outdoor-air intake rates between minimum and maximum levels to prevent the delivered air from being cooler than the supply-air set point.

Conversely a nonintegrated economizer does not operate when the mechanical cooling system is operating. If outdoor conditions are not sufficiently favorable to allow 100% economizing, no economizing is used. A two-stage thermostat often controls a nonintegrated economizer. The first stage opens the economizer; the second stage locks out the economizer and turns on the mechanical cooling.

6.2 Types of Air-Handling Systems Supported

The OAE tool supports the following types of single-duct air handlers:

- Constant-air-volume systems

- Variable-air-volume (VAV) systems with no volume compensation (i.e., outside-air intake is a constant fraction of the supply-air flow rate rather than changing it to maintain a constant outside-air volume).

Air handlers that the OAE tool does <u>not</u> support include:

- VAV systems that maintain constant outside-air volume flow through volumetric flow measurements (commonly using air-monitoring stations consisting of pitot-tube arrays)

- VAV systems that attempt to approximately provide constant outside-air volumetric flow by increasing the outside-air fraction (e.g., by opening the outside-air damper system) as the fan speed decreases

- Systems that utilize CO_2-based outside-air control strategies

- Dual-duct air-handling systems.

6.3 Metered Data Requirements for the OAE Module

The OAE requires seven periodically measured/collected (currently at sub-hourly increments) variables, as shown in Figure 2 (bold labels in the figure identify required data). In addition to the seven variables, the damper-position signal is also required for air handlers with damper-position-signal control, i.e., if the damper-position signal is controlled directly to maintain the ventilation or to control the supply- or mixed-air temperatures when the air handler is economizing. For economizers with enthalpy-based control, outside- and return-air relative humidity (only for differential enthalpy control) or dew-point temperatures are required. If the supply- or mixed-air temperature set point is reset, the reset value at each hour is also needed.

6.4 Setup Data Requirements

The OAE module requires several one-time (setup or configuration) data inputs to characterize the existing systems and how they are controlled. In addition to the setup data, the OAE also requires at least seven metered data points (same as variables called out in Figure 2). The engineering units for all inputs (both setup and measured) are assumed to be in Inch-Pound units unless otherwise specified.

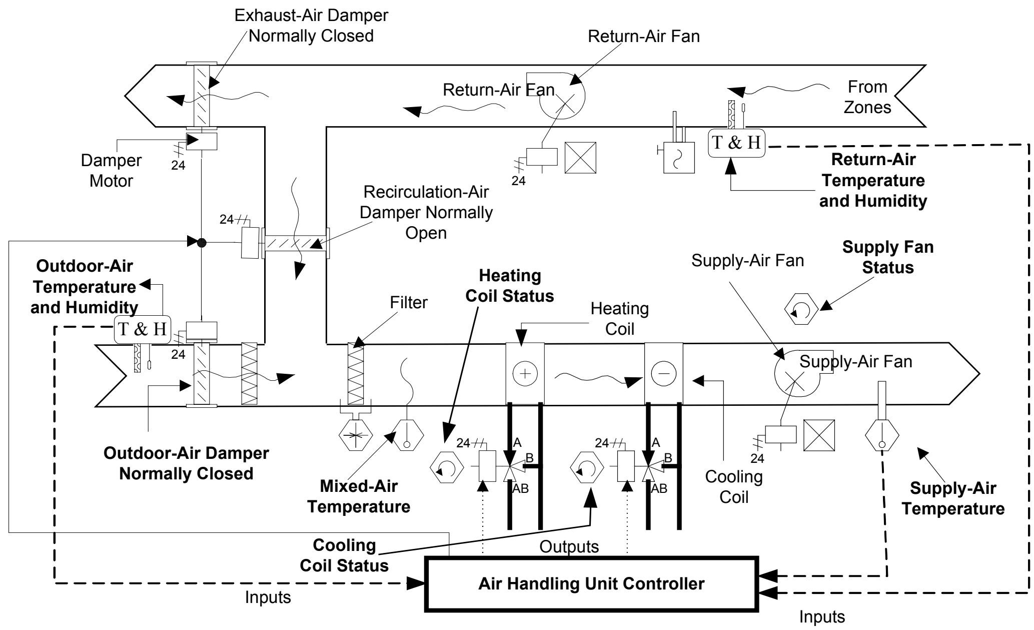

Figure 2 – Schematic Diagram of an Air Handler Showing the Sensor Locations

The OAE is capable of detecting and diagnosing faults with most commonly found air handlers using almost all outside-air and economizer control strategies. However, the user must describe the control strategies used to the OAE with the setup information. In addition, the OAE is designed to be flexible in accepting status inputs. For example, the WBD can accept any one of four different types of signals to indicate whether the supply fan is ON. Once the OAE module is configured, the detection and diagnosis is fully automated.

The setup data are required for all air-handler systems with economizers. These data describe:

1. The basic air-handling system
2. The minimum, maximum, and required (building fully-occupied) outdoor-air fractions
3. The occupancy schedule, defining when the required outdoor air must be supplied
4. Data needed to estimate energy and cost impacts of problems.

There are 17 items of user-supplied setup data that must be supplied for every air-handler system. In addition, there are a number of additional setup data inputs, along with the types of air handler and economizer controls to which they are applied. As few as 3 to as many as 15 additional inputs may be required to describe any given system type. For a typical system with an outdoor-air-fraction-based differential temperature economizer with low-limit control, nine of these setup items are required. Almost all of these inputs are provided with defaults that enable the OAE module to be initialized without the user providing them; however, it will not provide correct diagnoses unless the setup values are correct. Potential errors in the setup data are sometimes identified by the OAE as candidate causes of problems it detects with the air-handler operation. Generally, these then need to be reconciled by the building operator and setup data changed to correct any differences between the actual and default values.

6.5 Basic Operating Sequence of Air Handlers

The OAE module uses a logic tree to determine the operational "state" of outdoor-air ventilation and economizer systems at each point in time for which measured data are available. The logic tree is based on the basic air-handler operating sequence, as described below.

An air handler typically has two main controllers: 1) to control the outdoor-air intake and 2) to control the supply-air temperature (in some cases mixed-air temperature is controlled rather than supply-air temperature). The basic operation of the air handler is to draw in outdoor air and mix it with return air from the zones and, if necessary, condition it before supplying the air back to the zones, as shown in Figure 2.

An air handler typically has four primary modes of operation during a building's occupied periods, for maintaining ventilation (fresh-air intake) and comfort (the supply-air temperature at the set point), as shown in Figure 3. The operating sequence determines the mode of operation and is based on the ventilation requirements, the internal and external thermal loads, and indoor and outdoor conditions.

When indoor conditions call for heating, the heating-coil valve is modulated (i.e., controlled) to maintain the supply-air temperature at its set point (heating mode in Figure 3). When the air handler is in the heating mode, the cooling-coil valve is fully closed, and the outdoor-air damper is positioned to provide the minimum outdoor air required to satisfy the ventilation requirements. As heat gains increase in the zone and the need for cooling increases, the air handler transitions from heating to cooling. Before mechanical cooling is provided, the outdoor-air dampers are opened fully to use the favorable outdoor conditions to provide 100% cooling (economizer mode in Figure 3). In this mode, the heating- and the cooling-coil valves are fully closed and the outdoor-air dampers are modulated to meet all the cooling requirements.

As the heat gains in the zone continue to increase, the outdoor air alone cannot provide all the cooling necessary, and the air handler changes modes by initiating mechanical cooling (cooling and economizing mode in Figure 3) to supplement the economizer. In this mode, the outdoor damper is fully open, the heating-coil valve is fully closed, and the cooling-coil valve is modulated to maintain the supply-air temperature. As the outdoor conditions become unfavorable (i.e., too hot and humid) for economizing, the air handler changes mode again. This time the outdoor-air dampers are modulated to the minimum position to provide the minimum outdoor air required to satisfy the outdoor-air ventilation needs, the heating-coil valve continues to be fully closed, and the cooling-coil valve is modulated to maintain the supply-air temperature at its set point.

If an air handler does not have an economizer, there are two basic modes of operation (heating and mechanical cooling). If the economizer is not integrated with mechanical cooling (i.e., it cannot economize and provide mechanical cooling simultaneously), there are three basic modes of operation (heating, economizing, and mechanical cooling).

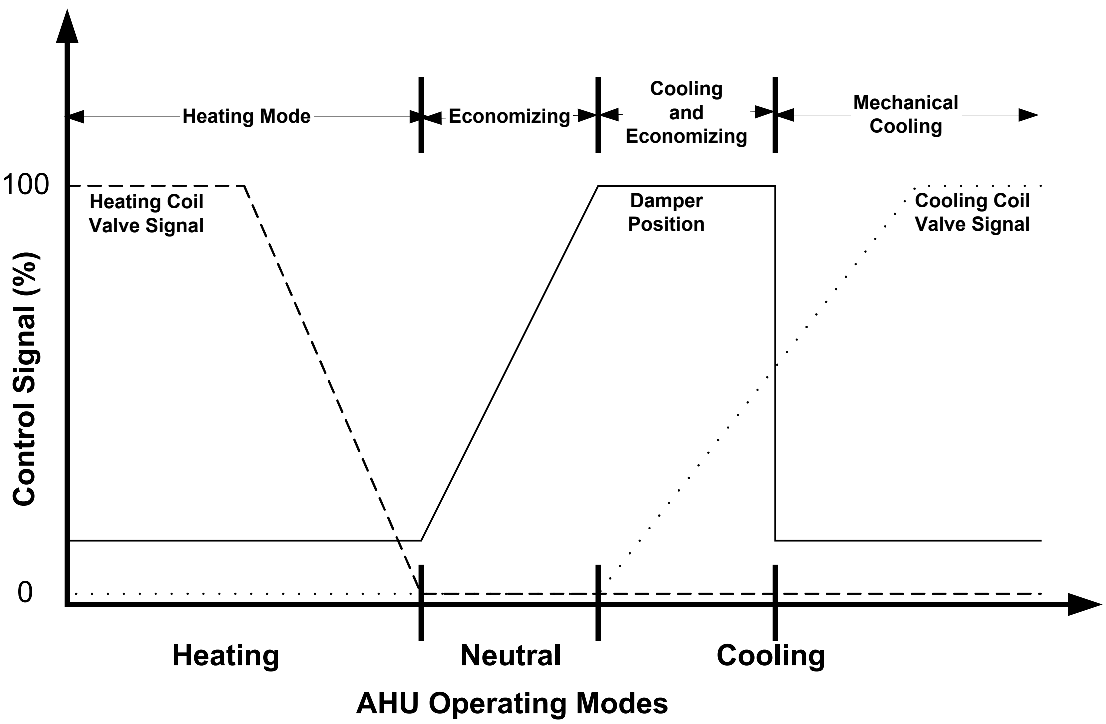

Figure 3 – Basic Operating Sequence of an Air-Handling Unit

6.6 Diagnostic Approach

The OAE uses rules derived from engineering models and understanding of proper and improper air-handler performance to diagnose operating conditions. The rules are implemented in a decision tree structure in the software. The OAE diagnostician uses periodically measured conditions (temperature or enthalpy) of the various airflow streams, measured outdoor conditions, and status information (e.g., fan on/off status) to navigate the decision tree and reach conclusions regarding the operating state of the air handler. At each point in the tree, a rule is evaluated based on the data, and the result determines which branch the diagnosis follows. A conclusion is reached regarding the operational state of the air handler when the end of a branch is reached. Tolerances are assigned to each data point, and uncertainty is propagated through all calculations.

Many of the states correspond to normal operation and are dubbed "OK states." For example, one OK state is described as "ventilation and economizer OK; the economizer is correctly operating (fully open), and ventilation is more than adequate." For this case, the system is apparently operating correctly with the outdoor-air damper fully open to benefit to the maximum extent possible from cool outdoor-air used for free cooling. Ventilation rates for the occupants are also being met by the current outdoor-air ventilation rate. Other states correspond to something operationally wrong with the system and are referred to as "problem states." An example problem state might be described as "economizer should not be off; cooling energy is being wasted because the economizer is not operating; it should be fully open to utilize cool outside air; ventilation is adequate." As with the previous state, conditions are such that the outside-air damper should be fully open to benefit from free cooling; however, in this case the economizer is incorrectly off, yet the outdoor-air ventilation is still adequate to meet occupant needs. Thus, the building is experiencing an energy penalty from not using the economizer. Other states (both OK and problem) may be tagged as incomplete diagnoses, if critical data are missing or results are too uncertain to reasonably reach a conclusion.

Each problem state known by the OAE module has an associated list of possible failures that could have caused the state; these are identified as possible causes. In the example above, a stuck outdoor-air damper, an economizer controller failure, or perhaps a mis-configured setup could cause the economizer to be off. Thus, at each metered time period, a list of possible causes is generated.

An overview of the logic tree used to identify operational states and to build the lists of possible failures is illustrated in Figure 4. The boxes represent major sub-processes necessary to determine the operating state of the air handler; diamonds represent tests (decisions), and ovals represent end states and contain brief descriptions of OK and problem states. Only selected end states are shown in this overview, and the details of processes and decisions are excluded because of space constraints.

6.7 Basic OAE Functionality

The OAE user interface uses color-coding to alert the building operator when problems occur. It then provides assistance in identifying the causes of the problems detected and in correcting them. Figure 5, for example, shows a representative OAE diagnostician window. On the left pane of the window is a directory tree showing the various systems implemented in this particular WBD system. The tree can be used to navigate among the diagnostic results for various systems. In this case, results for air handler 12 (AHU-12) are highlighted in the tree. In the right pane is a color map, which shows the OAE diagnostic results for this air handler. Each cell in the map represents an hour. The color of the cell indicates the type of state. White cells identify OK states, for which no problems were detected. Other colors represent problem states. "Clicking" the computer mouse on any shaded cell brings up the specific detailed diagnostic results for that hour.

Figure 6 and Figure 7 show pop-up windows providing a short description of a problem, a more detailed explanation of the problem, energy impacts of the problem, potential causes, and suggested actions to correct each cause. The second window (Figure 7) labeled “Details” is revealed by "clicking" on the "Details" button in the first window (Figure 6). In this case, the problem investigated is a sensor problem. The current version of this OAE diagnostician cannot, by itself, isolate the specific sensor that has failed, but instead it suggests manual inspection and testing of the sensors and their wiring to identify the specific problem. Yet another example of OAE is shown in Figure 8, where a high-energy consumption problem is evident.

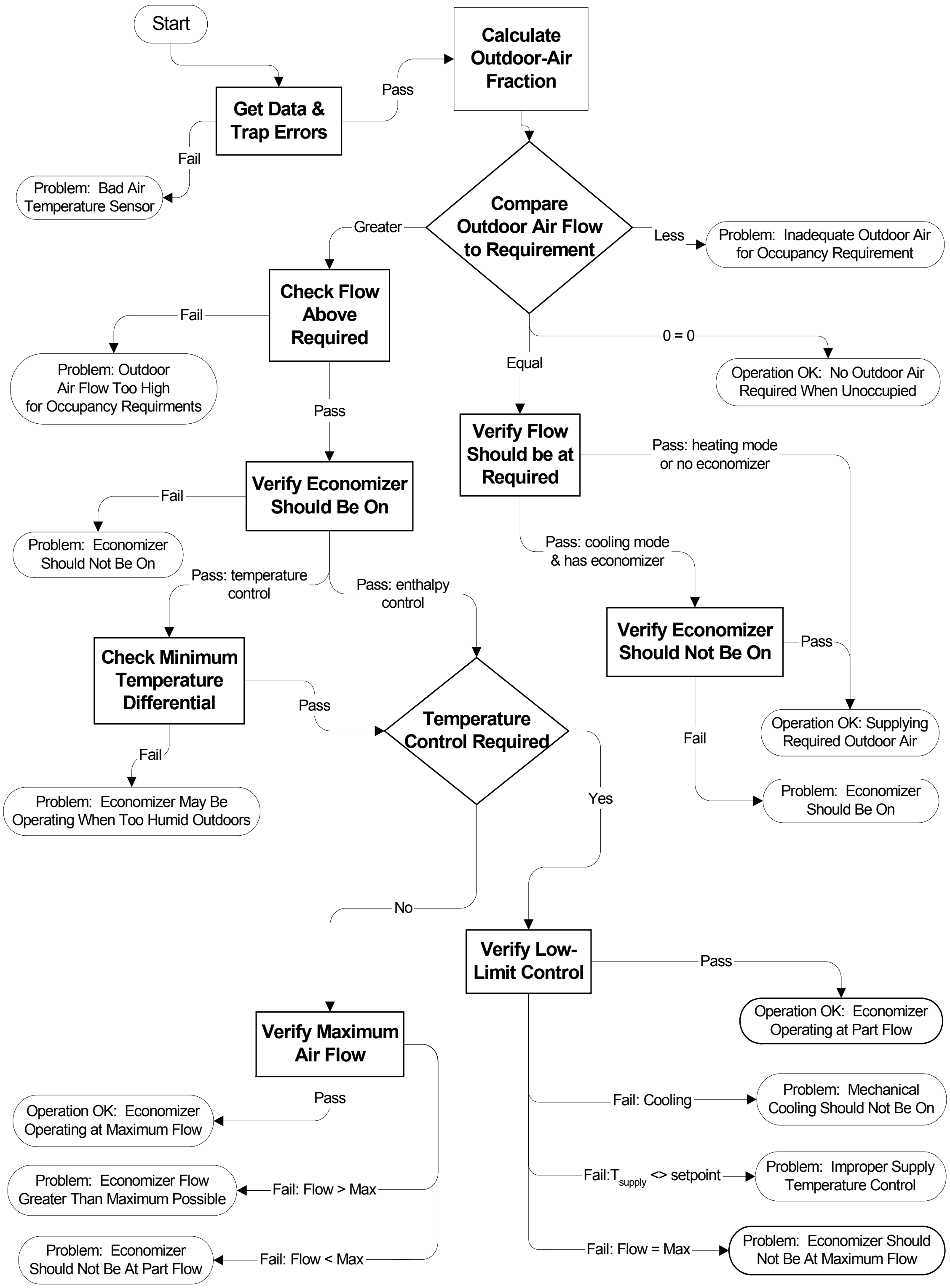

Figure 4 – Overview of the OAE Diagnostic Logic Tree Showing Key Decision Processes in Boxes and Operating States in Ovals

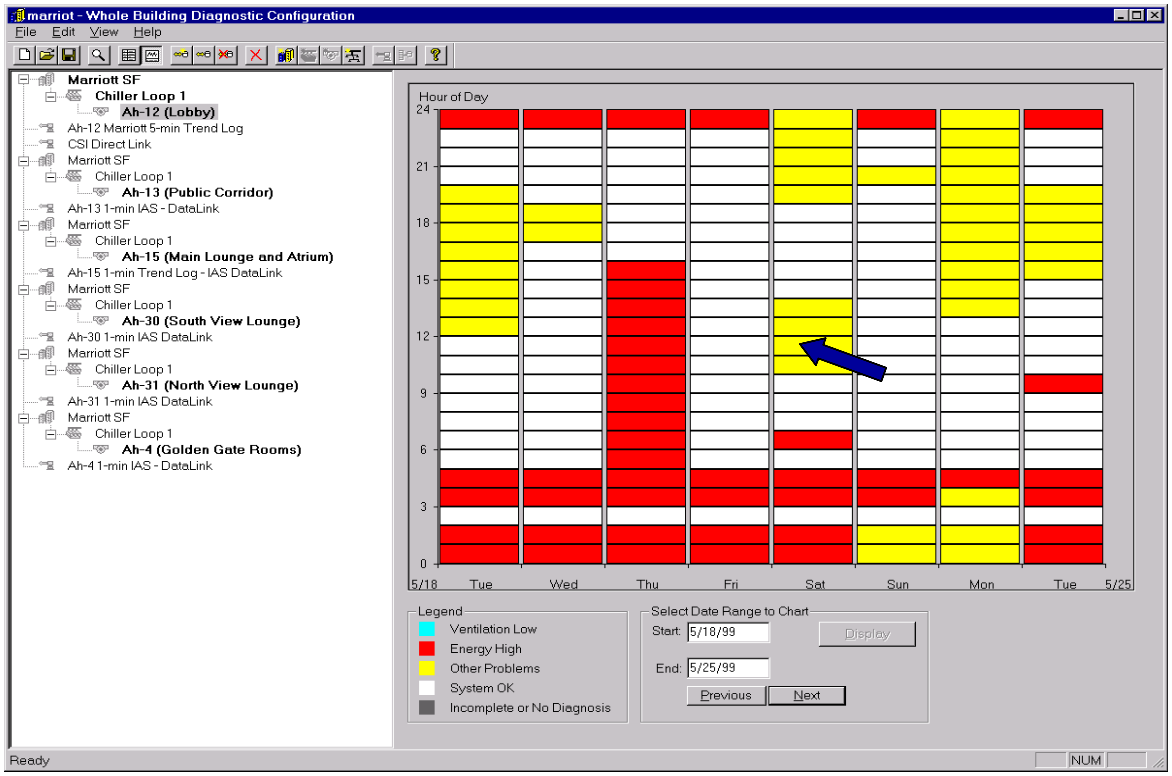

Figure 5 – Diagnostic Results Showing Proper and Faulty Operation for an Air Handler with a Faulty Outdoor-Air Temperature Sensor. The arrow identifies the cell for which more detailed results are given in Figure 6 and Figure 7

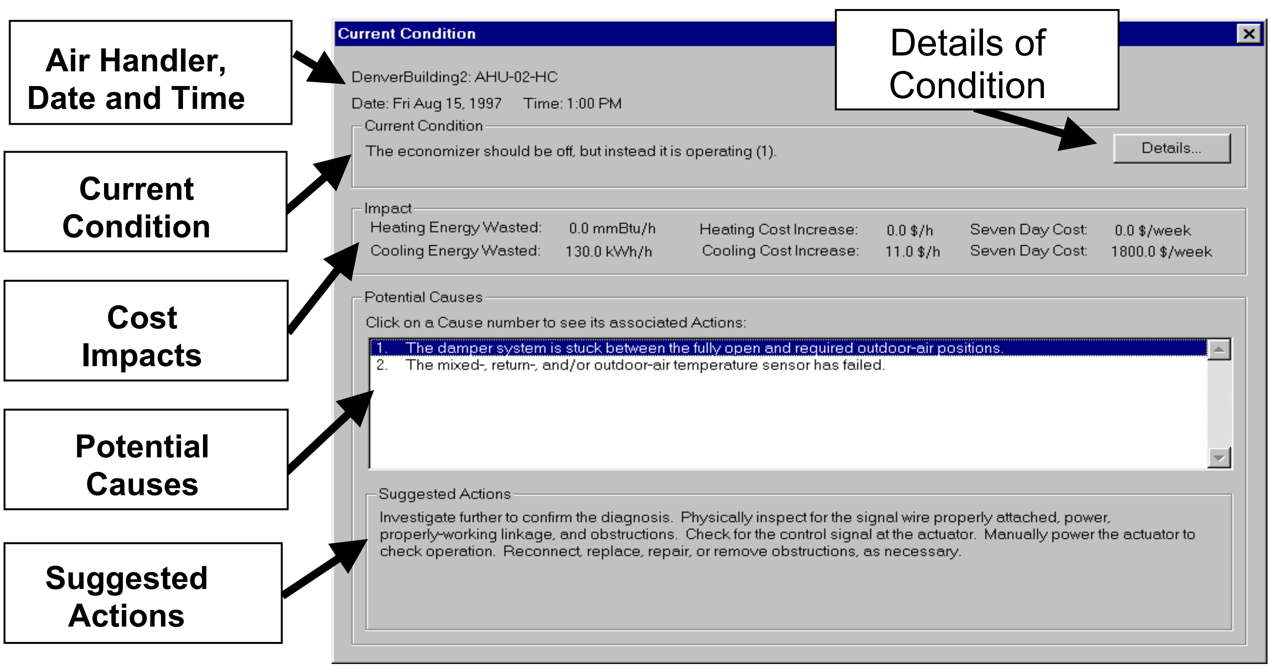

Figure 6 – Window Showing a Description of the Diagnosis, the Impacts of the Problem Found, Potential Causes of the Problem, and Suggested Corrective Actions.

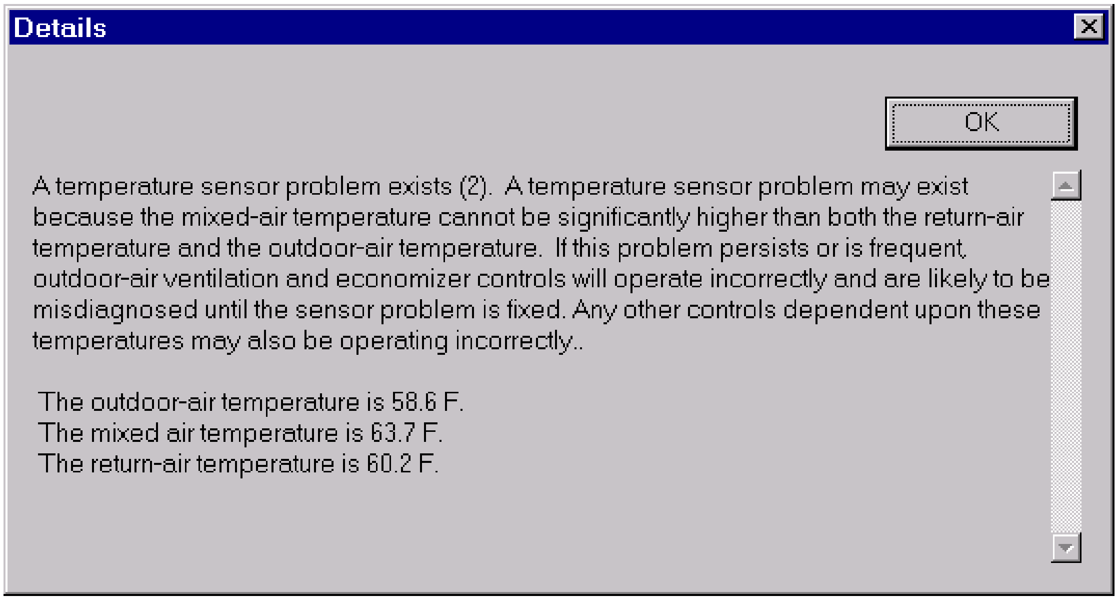

Figure 7 – "Details" Window Showing a Detailed Description of the Temperature Sensor Problem Identified in Figure 5

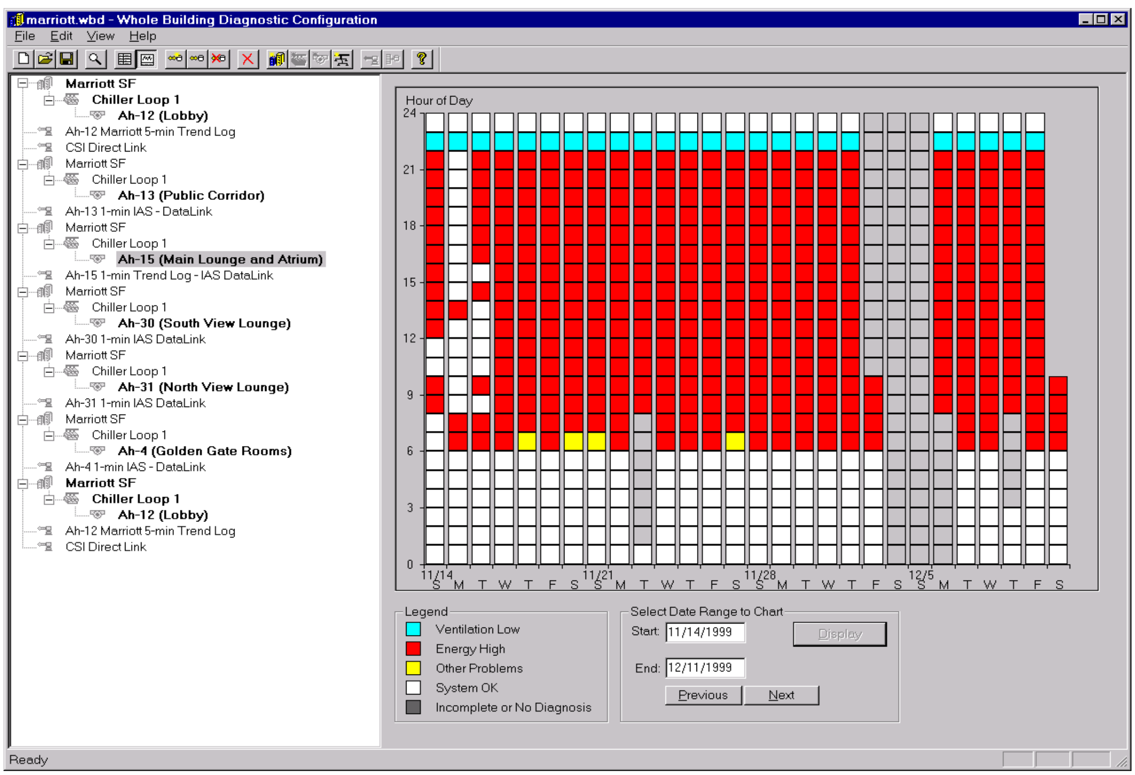

Figure 8 – An Example OAE display is shown for Air Handler 15 for November 14 through December 11, 1999. A high-energy consumption problem is clearly evident throughout this time period.

6.8 Requirements for Using the WBD and OAE

The WBD and its diagnostic modules were developed for a personal computer running any Microsoft Windows operating system (98/ME/NT/2000/XP)[3]. The WBD can be run in a fully automated/unattended mode or can be used to batch process the data. To run the WBD in a fully automated (unattended) mode, the data collection from the air handlers to the WBD database must be fully automated. A companion data collection module can be used to collect the data from air handlers that are controlled by central building automation systems. To use this data collection module, the site needs a networked computer operating under Windows 98/NT/2000 (preferably NT or 2000 to avoid problems with the computer's clock) and a building automation system (BAS) that support Microsoft DDE protocols. There are other methods available for data collection; however, several of the current methods may require increased levels of human intervention (see Figure 1).

Although the underlying methodology used by the OAE is independent of the time interval at which data are collected, the user interface can only display results at hourly intervals. Therefore, all data should be at least at an hourly resolution. The data collection module can process data that is more frequent (5-minute intervals, for example) and average it to hourly values. Instantaneous values obtained on 5-minute intervals or less, and averaged to form hourly data, are recommended. It is preferable to have all measured data either instantaneous or averaged. Mixing instantaneous and averaged data may introduce false alarms and therefore is not recommended.

[3] Although the initial version of the WBD and its components were developed and tested under the Windows 95 operating system, this operating systems in not currently supported.

7 Summary of Off-line Results for Alameda County Courthouse

The data for the off-line test, for one air handler at the Alameda County Courthouse, was collected using the trending feature of the existing building automation system in Alameda County. The data collection was from February 8, 2001 through February 23, 2001 collected on 5-minute intervals, with only a couple one or two-hour gaps (3 p.m. to 4 p.m. on February 8, 2001 and 12 p.m. to 1 p.m. on February 16, 2001). A typical section of the data after it was assembled into a single file is shown in Table 3. The column names are the sensor and control point names used in the CSI control system.

There were two problems identified in the data delivered to us. The supply-air temperature file had a recurring pattern of data duplication due to an unknown cause. These repeated stretches of data were manually eliminated for the off-line analysis.

The second problem was that the mixed-air temperature setpoint values (MA Setpt in Table 3) were all either zero or missing. The mixed-air temperature setpoint is used to modulate, or throttle, the outdoor-air dampers during the economizer mode so that the supply air is not too cold and requires heating. If this setpoint (or the supply-air temperature setpoint for the air handler) is dynamically reset by the control system instead of being constant, the OAE diagnostic module requires it as input data from the control system so the correct value is used in the diagnoses at any given time. Since this data was not present, the off-line test was conducted with a fixed mixed-air temperature setpoint determined by observation from the data.

Table 3 – Typical Raw 5-Minute Data from AHU-1

Date	Time	MA Temp	OA Temp Lowest	RA Temp	SA Temp	CHW Coil	HW Coil	Duct Static	RA Flow	RAT Damp	OSA Dmpr	Econ	SA Flow	S1 Vane	SA Fan Status	RA Fan Status	MA Setpt	Avg Zone Temp
2/8/2001	15:05	62.94	55.08	71.55	65.14	24	0	2.656	87201	0	100	100	112490	13.2	1	1	0	71.33
2/8/2001	15:10	60.71	54.91	71.60	63.46	27	0	2.200	86812	39	61	61	107713	12.8	1	1		71.33
2/8/2001	15:15	61.83	55.08	71.60	65.71	0	0	2.677	86389	11	89	89	110379	12.2	1	1		71.33
2/8/2001	15:20	62.74	55.45	71.64	64.58	0	0	2.408	87225	4	96	96	111868	13.4	1	1		71.33
2/8/2001	15:25	59.58	54.68	71.67	63.19	0	0	2.366	87614	63	37	37	107075	12.2	1	1		71.33
2/8/2001	15:30	62.91	55.06	71.67	66.20	0	0	2.706	87267	0	100	100	113702	12.8	1	1		71.33
2/8/2001	15:35	61.29	54.46	71.69	63.97	0	0	2.224	87944	52	48	48	108469	12.6	1	1	0	71.46
2/8/2001	15:40	62.38	54.82	71.69	66.18	0	0	2.774	87267	0	100	100	113984	12.7	1	1	0	71.46
2/8/2001	15:45	60.37	54.30	71.71	62.22	0	0	2.247	86911	17	83	83	106486	13.0	1	1	0	71.46
2/8/2001	15:50	58.62	54.30	71.71	62.56	0	0	2.473	86975	46	54	54	106096	11.8	1	1	0	71.46
2/8/2001	15:55	62.82	53.91	71.64	64.74	25	0	2.605	87685	0	100	100	113621	13.3	1	1	0	71.46
2/8/2001	16:00	60.17	53.31	71.65	63.32	28	0	2.295	88706	71	29	29	107661	12.6	1	1	0	71.46

Heading definitions:

MA: mixed-air.
OA: outdoor-air.
RA: return-air.
SA: supply air.
CHW: chilled water (percentage open for the chilled water valve.
HW: hot water (percentage open for the hot water valve.
RAT: return air damper position.
OSA: outdoor air.
Econ: economizer (percentage of fully open for the current outdoor-air damper position (100 corresponds to the maximum economizing possible).
S1: supply air.
Setpt: setpoint
Avg: average

7.1 Data Requirements

Air-handler (AHU-1) in the Alameda County Courthouse, was selected for the off-line test by Matt Muniz (Alameda County Energy Program Manager and WBD Administrator) because it was readily accessible and representative of the operation of other air handlers there. It is a variable-air-volume air handler with volume controlled by vanes.

A list of data points collected by Alameda County used by the OAE diagnostic module is shown in Table 4. Alameda County also provided supplementary data points not used by the OAE: duct static pressure, vane position, supply- and return-air flow rates, average zone temperature, and separate status signals for the supply, return, and relief fans. These data were collected as instantaneous values on five-minute intervals. The data were delivered in *diff* (data interchange format) format files, one data channel per file. These were then combined into a single *diff* file with the proper WBD channel names as column headings. They were then read in and integrated to form hourly averages by the WBD's data collection module. Integration of most channels is conditional on whether the fan is on or not, as shown in Table 4. This process also places them in the *AhuData* table of the WBD database for subsequent processing by the OAE module.

Table 4 – Data Points Collected by Alameda County for OAE Diagnostic Module

Type of Data	Data Item	Units	Integration
time stamp	time stamp (end of hour)	Date Time	none
fan on-time	fan on-time	Fraction	average hourly
air temperatures	outdoor-air (dry-bulb) temperature	°F	average hourly when fan on
	return-air (dry-bulb) temperature		
	mixed-air (dry-bulb) temperature		
	supply-air temperature (dry-bulb)		
damper position	outdoor-air damper position command	% open	average hourly when fan on
status of AHU	hot-water valve position (fraction open)	% open	average hourly when fan on
	chilled-water valve position (fraction open)		
control setpoints	mixed-air temperature setpoint	°F	average hourly when fan on

7.2 Configuring the Diagnostician

The next step in conducting the off-line analysis was to specify the air handler's configuration for the WBD's OAE diagnostic module. There are two aspects of the air handler's operation that must be specified for the OAE: the control strategy for the outdoor-air and economizer, and the schedule (times of day and days of week) for which the minimum outdoor air must be supplied for the occupants.

A screenshot of the configuration screen of the WBD's user interface is shown in Figure 9. The left side is the hierarchical "configuration tree" specified by the Administrator for this WBD installation. In this case it is the Alameda County Courthouse and a data collection network at the highest level. Beneath the building is a heating/cooling plant, and the plant serving the air handlers. In the off-line test only one air handler (AHU-1) is configured. When the user selects

AHU-1 and the configuration tab on the toolbar is pushed, as shown, the configuration for AHU-1 is displayed as shown.

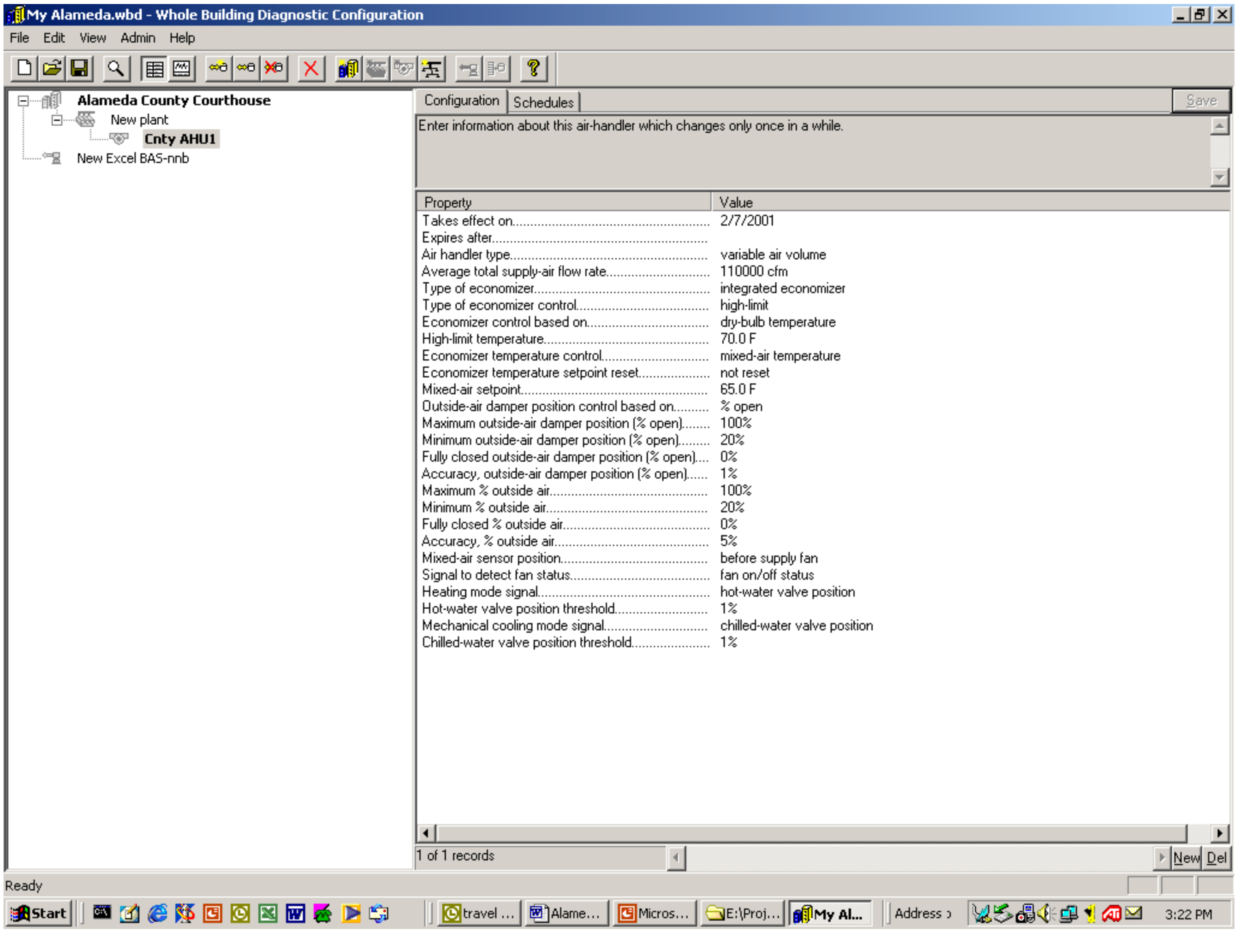

Figure 9 – WBD's Air Handler Configuration Screen for AHU-1

7.3 Air Handler Configuration Parameters

The configuration parameters for AHU-1 are shown in Figure 10. The air handler is a variable-air-volume type with a maximum rated flow of about 110,000 ft^3/min. It has an integrated, high-limit economizer based on temperature. The high limit for economizer operation is 70^{o}F, with a constant mixed-air temperature setpoint of 65^{o}F (assumed because of the data collection problem discussed above).

Enter information about this air-handler which changes only once in a while.

Property	Value
Takes effect on	2/7/2001
Expires after	
Air handler type	variable air volume
Average total supply-air flow rate	110000 cfm
Type of economizer	integrated economizer
Type of economizer control	high-limit
Economizer control based on	dry-bulb temperature
High-limit temperature	70.0 F
Economizer temperature control	mixed-air temperature
Economizer temperature setpoint reset	not reset
Mixed-air setpoint	65.0 F
Outside-air damper position control based on	% open
Maximum outside-air damper position (% open)	100%
Minimum outside-air damper position (% open)	20%
Fully closed outside-air damper position (% open)	0%
Accuracy, outside-air damper position (% open)	1%
Maximum % outside air	100%
Minimum % outside air	20%
Fully closed % outside air	0%
Accuracy, % outside air	5%
Mixed-air sensor position	before supply fan
Signal to detect fan status	fan on/off status
Heating mode signal	hot-water valve position
Hot-water valve position threshold	1%
Mechanical cooling mode signal	chilled-water valve position
Chilled-water valve position threshold	1%

Figure 10 – Configuration Parameters for AHU-1

For AHU-1, the outdoor-air damper system is controlled based on a specification of damper position (% open), with a minimum position during occupied hours of 20%, a maximum position of 100% during economizer operation, and a fully closed position that was not observed in the data provided but is presumed to be 0%. The damper position is assumed accurate to within 1% (one percentage point). These damper positions were specified as corresponding to outdoor-air fractions of 100%, 20%, and 0%, respectively. Only the 20% value was observed in the data analyzed. The resulting outdoor-air fractions computed by the OAE diagnostic module from the air temperatures were observed to be accurate to within about 5%

The remaining parameters specify the types of signals and thresholds used to determine whether the supply fan and heating and cooling modes for the air handler are on at a given time.

7.4 Air handler Outdoor-Air Schedule

The operating schedule of AHU-1 was established by observing the off-line monitored data. The supply-air fan was operating at 100% consistently between 7 a.m. to 7 p.m. 5 days a week, about 20% of the time between 4 a.m. and 6 a.m., and about 40% of the time from 7 p.m. through 9 p.m. On Sundays, it operated at 100% consistently between 9 a.m. and 5 p.m. The supply-air fan was not operating on Saturdays.

This schedule was used for the off-line analysis. It appears that there is a means by which heating/cooling/ventilation services can be requested during off hours by the occupants, so some erratic detection of inadequate outdoor-air by the OAE module is expected in the off-line analysis.

7.5 Off-line Test Results

The OAE diagnostic results for the off-line period are shown in Figure 11.   This view is displayed when the user selects AHU1 on the configuration tree on the left side of the screen and pushes the *View diagnostic results* button on the toolbar. Each square of the "checkerboard" displays the diagnostic results for an hour, and each column of squares are the hours in one day. Each square is color coded to indicate the general category of problem identified that hour, if any. As indicated in the legend in the lower part of the display, white squares indicate no problem is detected. This was the case most of the time for AHU-1. Grey cells indicate that full diagnosis could not be completed, generally due to missing data. Clicking on both of the gray cells in this case brings up a summary of the current condition that indicated the damper position data are missing or bad.

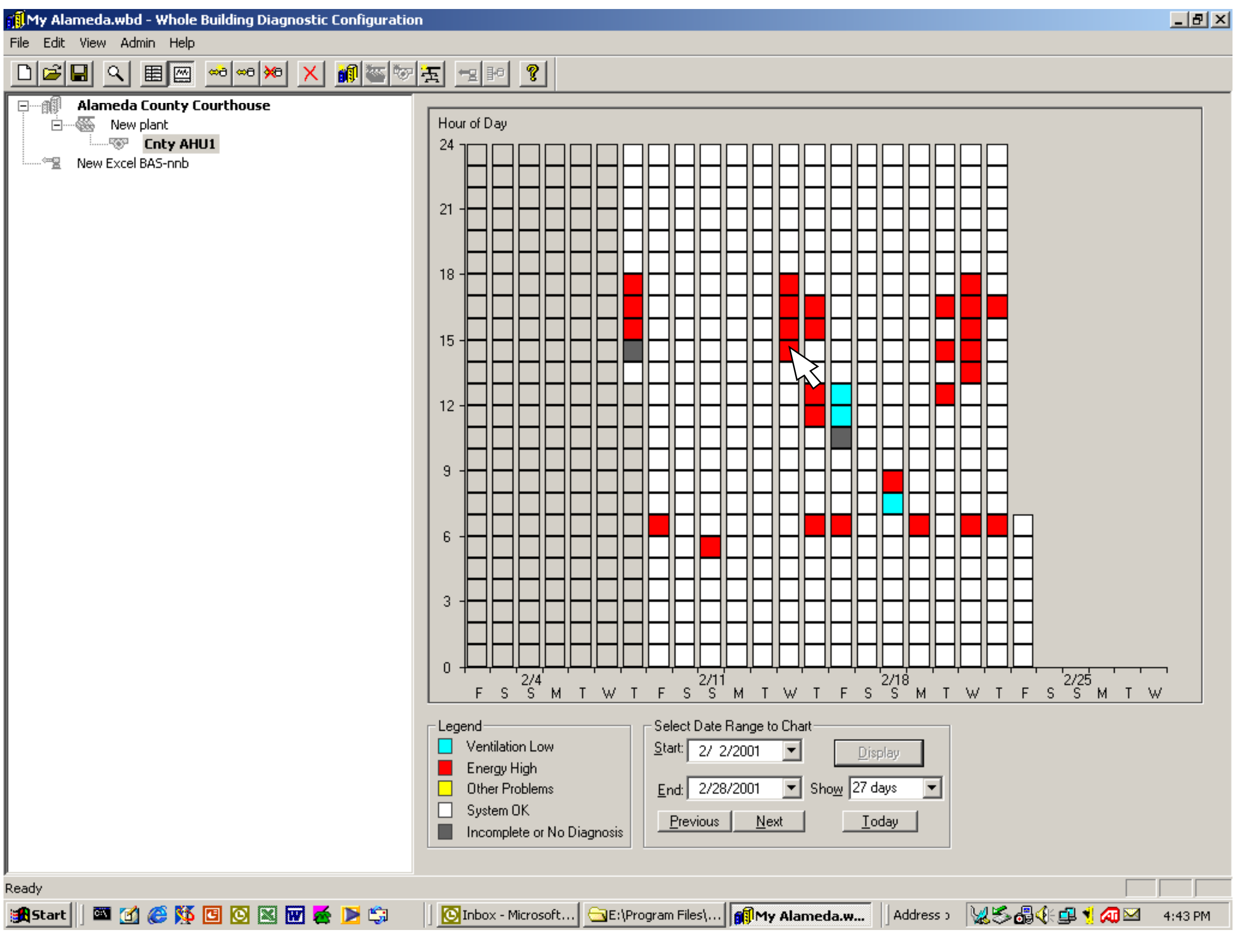

Figure 11 – WBD's Diagnostic Results View for AHU-1 at Alameda County

Problems are indicated by color squares. The blue squares indicate inadequate outdoor ventilation air is being supplied for the occupants. Two of these are likely false alarms, probably the result of problems that interrupted the data collection (the only data provided was the supply fan status, and this was off for these times). The other blue square was caused by a discrepancy between the scheduled and actual operation of the system. This was anticipated, as discussed at the beginning of **Section 5**.

There a number of red squares during the off-line testing period of AHU-1 representing problems that waste energy. As shown in Table 5 the red squares occur 8% of the time during the period analyzed, and are investigated in further detail here.

Table 5 – Frequency of Problems for AHU-1 During Offline Testing

Category of Operational States	Number of Occurrences	Fraction of Total Hours	Reliability Score
Operation OK	321	91%	95%
OK but incomplete	2	1%	96%
Inadequate Ventilation	3	1%	100%
Excess Ventilation	0	0%	NA
Low Economizer Flow	0	0%	NA
High Economizer Flow	0	0%	NA
Control Problems	28	8%	94%
Control Problems	0	0%	NA

Clicking on the red cell with the cursor pointed at it in Figure 11 brings up the *Current Condition* dialogue shown in Figure 12. The problem is indicated as "mechanical cooling is on but should be off." By browsing the other red squares, it was found that this message is common to virtually all of them. The cost impact estimates presented for most energy waste problems identified are not available for control problems such as this one, because estimating their impact is too complicated for the current version of the WBD's OAE diagnostic module.[4] A number of

[4] In general, the WBD cannot compute energy waste and cost impacts for temperature sensor or control problems, because the exact nature and magnitude of the problem must be clarified first. For the case illustrated here, the cooling does not need to be on, but the economizer does need to be throttled to control the supply temperature. Thus, the economizer is handling all the cooling load it can, and should. So, the error can't be calculated from the air-side conditions, and can only be estimated as the cooling being supplied from the chilled water flow, which we do not have available in the WBD at present.

There are exceptions to this, however. The report on the offline analysis at Symphony Towers (*Project 2.4 – Demonstration of the Whole-Building Diagnostician, Task 2.4.1 – Single-Building Operator Demonstration – Offline Test*) is one such case, with only a subtle difference from this one. In that case, although the *Current Condition* statement is the same as this one, the *Details* dialogue reveals that the outdoor-air temperature is low enough (below the supply air setpoint) to handle the entire cooling load. In this situation, assuming there is indeed a control problem as stated, the impact can be possible causes for this problem are presented; clicking on one of them (as shown) produces cursory guidance to the operator in the form of suggested action(s) that might be taken to verify and correct the problem.

Clicking on the *Details* button provides additional information on the nature of the problem, as shown in Figure 13. This provides a more detailed description of the problem, and some key data to help interpret it. The economizer is operating only partially open (around 50%), since the mixed-air temperature is about half way between the return- and outdoor-air temperatures. But mechanical cooling is on, and doesn't need to be since the outdoor air is cool enough (53°F) for the economizer to provide all the necessary cooling.

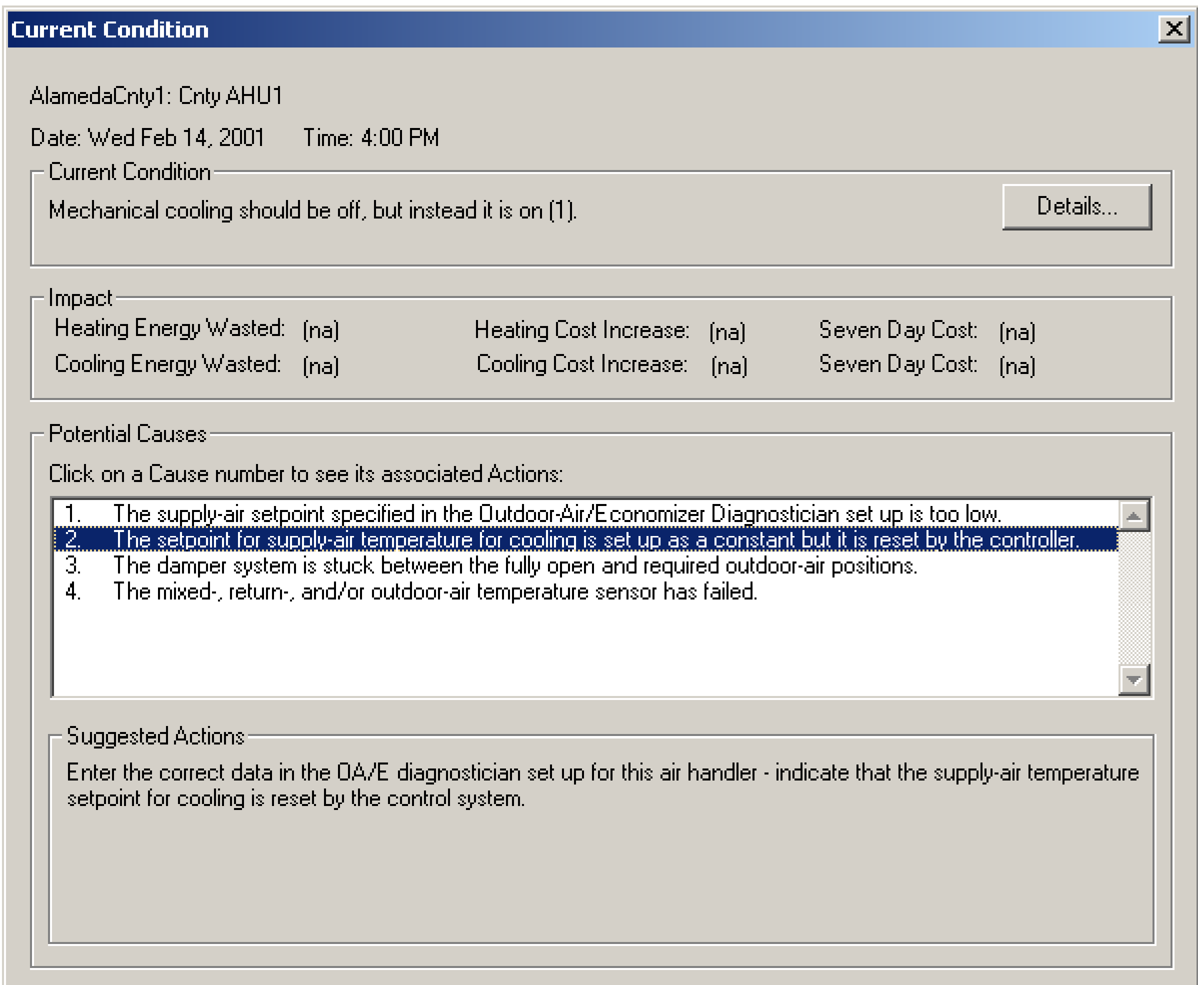

Figure 12 – Current Condition Dialogue for a Typical Red Square for AHU-1

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estimated entirely from sensor data from the airside flows.

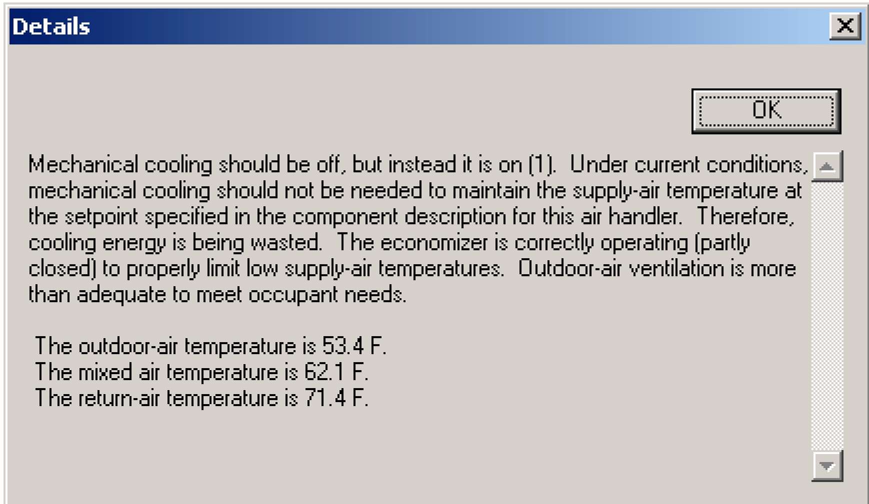

Figure 13 – Details on the Current Condition for a Red Square in AHU-1

7.6 Analysis of Trend Data

The user of the WBD is encouraged to utilize the control system's capabilities to investigate problems further when their exact nature or impact is unclear. In the off-line analysis, our version of this is to look at the raw data provided, which in fact is identical with trend log data obtained from the control system.

Examining the trend data showed that the supply-air temperature was being maintained at about 65°F, and the mixed air at about 63°F. Apparently, sometimes something such as excess fan heat or the outdoor-air dampers hunting for their setpoint causes the supply-air temperature to increase slightly above its setpoint, triggering the cooling valve to open to maintain the supply air at 65°F. This caused a small amount of unnecessary cooling during the period of the off-line analysis. It is unclear what the impact of this problem might be in the summer cooling season without more information on the setpoint-reset strategy employed for AHU-1.

7.7 Conclusions from Off-line Tests

The problem found in the operation of AHU-1 in the Alameda County Courthouse appears to be small, at least during the winter season. Most of the time the WBD's OAE diagnostic module indicates AHU-1 operates correctly. In fact, this is one of the best operating air handlers among the approximately 30 we have examined with the WBD.

All the required data for the OAE module appear to be available from the control-system sensors. No temperature-sensor errors were detected, suggesting that the sensors are providing reasonably accurate data.

The control system at the Alameda County Courthouse provided data fairly reliably, except for the mixed-air temperature setpoint. That issue, and whether the supply-air temperature setpoint is also reset and therefore required as an input, is the only procedural issues raised by the off-line analysis.

Matt Muniz, Don Lucas and their staff have been very cooperative and helpful in the conduct of this analysis, and we look forward to a productive demonstration of the WBD with them.

8 Summary of On-line Data Collection, Testing and Savings Opportunities

Continuous trend log data collection and testing started on OPMC AHU S-1 (February of 2001), OPMC AHU S-2 (May of 2001), HHOJ AHU S-1 (November of 2002) and HHOJ AHU S-2 (December of 2002) and continued through the end of the demonstration project. Due to a number of problems with the data collection, see **Section 8.2**, a number of gaps in the data was encountered. The off-line trend log data was also included and reprocessed in the OAE using the new air handler configurations set up in May of 2003. The three packaged AHU's at OES building were dropped from the on-line analysis because they did not have all the necessary data points to perform the diagnostics. Because the units were packaged direct-expansion units, the heating and cooling modes were not directly accessible through the building automation system. The AHU at EOC building lacked return-air temperature, which is a critical input required for diagnostics; therefore, it was dropped as well.

8.1 Configuring the Diagnostician

A screenshot of the configuration screen of the WBD's user interface for HHOJ AHU S-1 at Alameda County is shown in Figure 14**.** The configuration is typical for all four of the air handlers (HHOJ AHU S-1, HHOJ AHU S-2, OPMC AHU S-1 and OPMC AHU S-2) with the exception of airflow rates. The left side is the hierarchical "configuration tree," specified by the Administrator for a given WBD installation. In this case there is the HHOJ building and a data collection network at the highest level. Beneath the building designation (HHOJ) in the tree is a heating/cooling plant (Plant), which serves the air handlers. When the user selects AHU S-1 in the configuration tree, and the Configuration button on the toolbar is pushed, AHU S-1's configuration is displayed as shown.

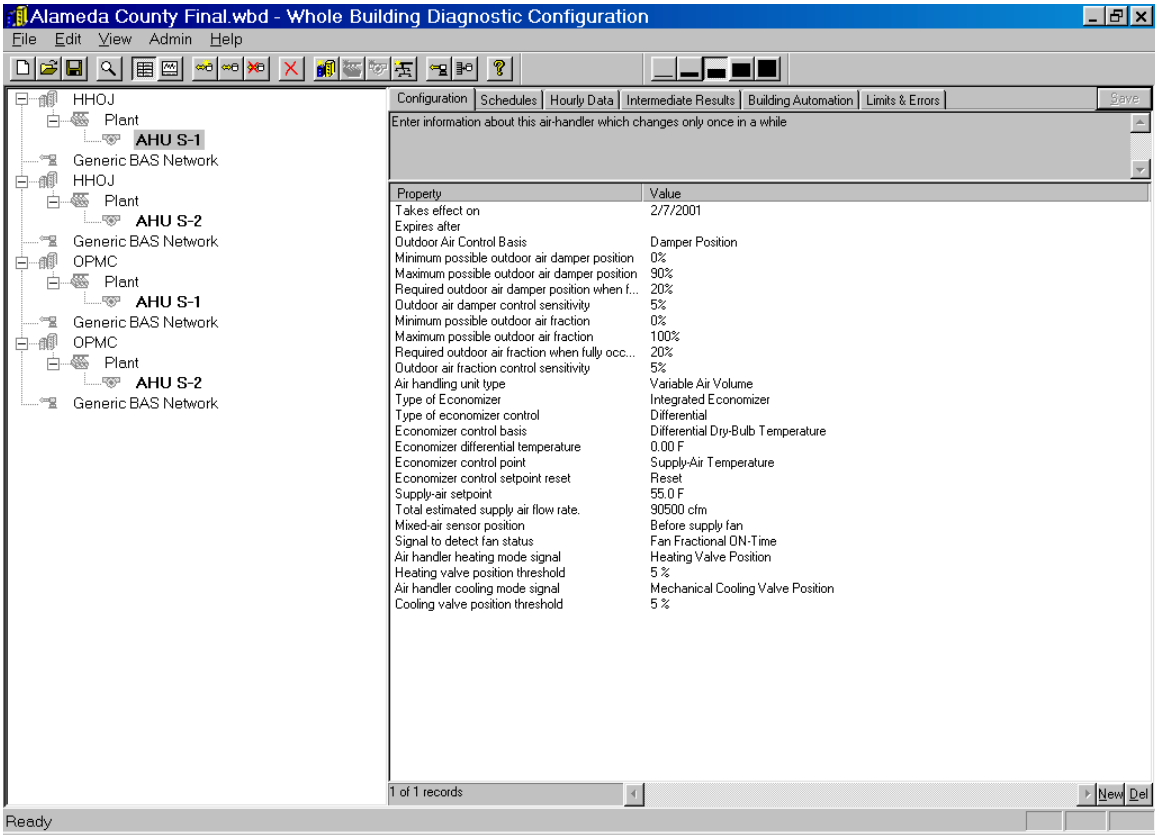

Figure 14 – Typical On-line Air Handler Configuration Screen (HHOJ AHU S-1 shown)

8.2 Data Collection

The WBD's automated on-line data collection module uses the Dynamic Data Exchange (DDE) protocol, an industry standard protocol developed by Microsoft, for exchanging data between two applications. Although the CSI control systems supported the DDE protocol, WBD's data collection module could not communicate with it directly. At the time of off-line testing CSI control system did not support the DDE protocol. The DDE protocol support was developed after Battelle and Alameda County made the request to the local controls vendor. It appears that the product may not have been fully tested before it was deployed at Alameda County. Battelle worked with the local controls vendor to resolve the problem, but was unsuccessful.

Therefore, Battelle had to develop an alternate automated data collection method for the Alameda County demonstration. The schematic of the automated process is shown Figure 15. The modified data collection process was successfully deployed at Alameda County. The process involves continuous collection of data from AHU's through the DDE portal from within Microsoft Excel spreadsheet. The data from the spreadsheet is read by another spreadsheet script and outputs the data into a file at every 5-minute interval (ALCOout.csv). The output data is delimited using a comma. The WBD's data collection module continuously scans the output file for new data and loads the data into the WBD database on a continuous basis as shown in Figure 15. With a few exceptions, the modified data collection worked fine.

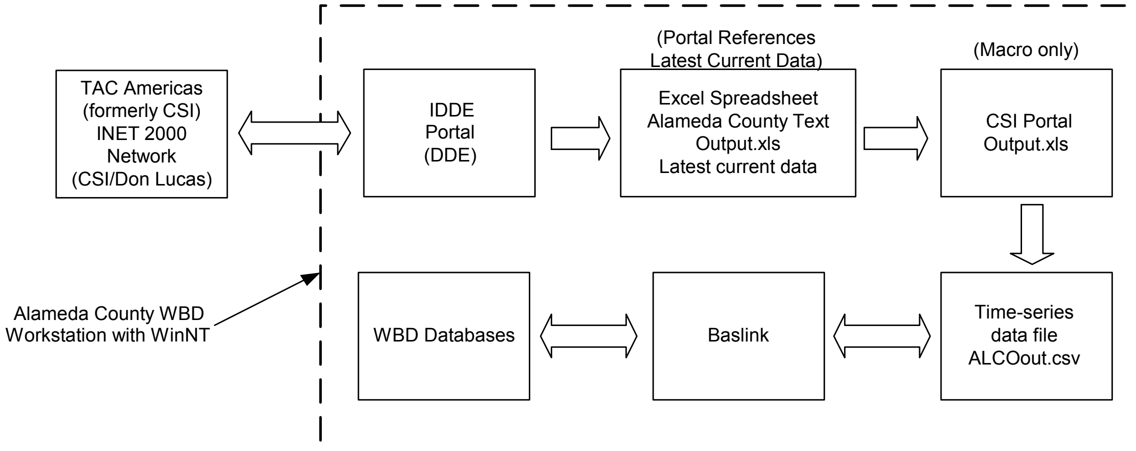

Figure 15 – Schematic diagram of the On-line Data Collection Process at Alameda County

The list of data points for each of the four AHU's at Alameda County is shown in Table 6. Integration of most channels is conditioned on whether the fan is on, as shown in Table 6.

Table 6 – Data Points Collected by Alameda County for OAE Diagnostic Module

Type of Data	Data Item	Units	Integration
time stamp	time stamp (end of hour)	Date Time	None
fan on-time	fan on-time	Fraction	average hourly
air temperatures	outdoor-air (dry-bulb) temperature	^oF	average hourly when fan on
	return-air (dry-bulb) temperature		
	mixed-air (dry-bulb) temperature		
	supply-air temperature (dry-bulb)		
air humidities	outdoor-air relative humidity	%	average hourly when fan on
	return-air relative humidity		
damper position	outdoor-air damper position command	% open	average hourly when fan on
status of AHU	chilled-water valve position (fraction open)	% open	average hourly when fan on

8.3 Results for HHOJ AHU S-1

The results from the WBD indicate that AHU S-1 is operating improperly. The screen shot of the processed results for the time period between May 4 and June 2, 2003 (most current), is shown in Figure 16. A significant number of the cells during occupied hours (5 a.m. to 7 a.m.) are red, followed in frequency by blue and gray. The red cells indicate energy waste with the blue cells, in most cases, indicating a problem with the temperature sensors (outdoor-air, return-air or mixed-air) or low ventilation.

Clicking on one of the red cells (hour 6 on May 6, 2003) displays the *Current Conditions Dialogue,* shown in Figure 17. The dialogue indicates, "Mechanical cooling should be off but instead is on" and provides a list of potential causes. By browsing the other red cells, this message was found to be common. Clicking on the *Details* button provides additional information on the nature of the problem, as shown in Figure 18. The Details dialogue indicates the outdoor-air temperature reading is (53.7°F), mixed-air temperature (56.8°F) and a return-air temperature of (71.2°F). It also provides a more detailed description of the problem, and some key data upon which detection of the problem is based. Review of the measured data can also help understand the problem better. In this case, the mixed-air temperature (56.8°F) is not nearly equal to the outdoor-air temperature (53.7°F) indicating that the damper may not be open fully. Although the OAE diagnostician has detected a problem, it cannot isolate the exact problem. However, during this occupied period, examination of the OAE hourly data has indicated the cooling valve is 25% open and the outdoor-air damper is in the 66% open position, as shown in Figure 19. During this period the cooling valve should be closed and the damper positioned to meet the supply-air set point. Upon further investigation of other red cells and associated hourly data indicates the chilled water valve and economizer damper, at the start of the occupied period (5 a.m.), both start in the 30% position and don't adjust properly until around 7 a.m. This positioning problem of the chilled water valve and damper was common throughout the demonstration period.

Clicking on one of the blue cells (hour 2:00 p.m. on May 28, 2003) displays the *Current Conditions Dialogue,* shown in Figure 20. The message in the dialogue indicates, "Inadequate outdoor-air ventilation is being supplied" and provides a list of potential causes. By browsing the other blue cells during the hours of 11:00 a.m. to 6:00 p.m., this message was found to be common. Clicking on the *Details* button provides additional information on the nature of the problem, as shown in Figure 21. This provides a more detailed description of the problem, and some key data upon which detection of the problem is based. Review of the measured data can also help understand the problem better. Although the OAE diagnostician has detected a problem with the low ventilation, it cannot isolate the exact problem.

The frequency of problems reported for AHU S-1 is shown in Table 7 (November 2002 through June 2003). The AHU S-1 unit operates about 10% of the occupied period with a control problem, 3% of the time with excess ventilation problem, 5% with inadequate ventilation and 6% with low economizer flow (economizer not fully open).

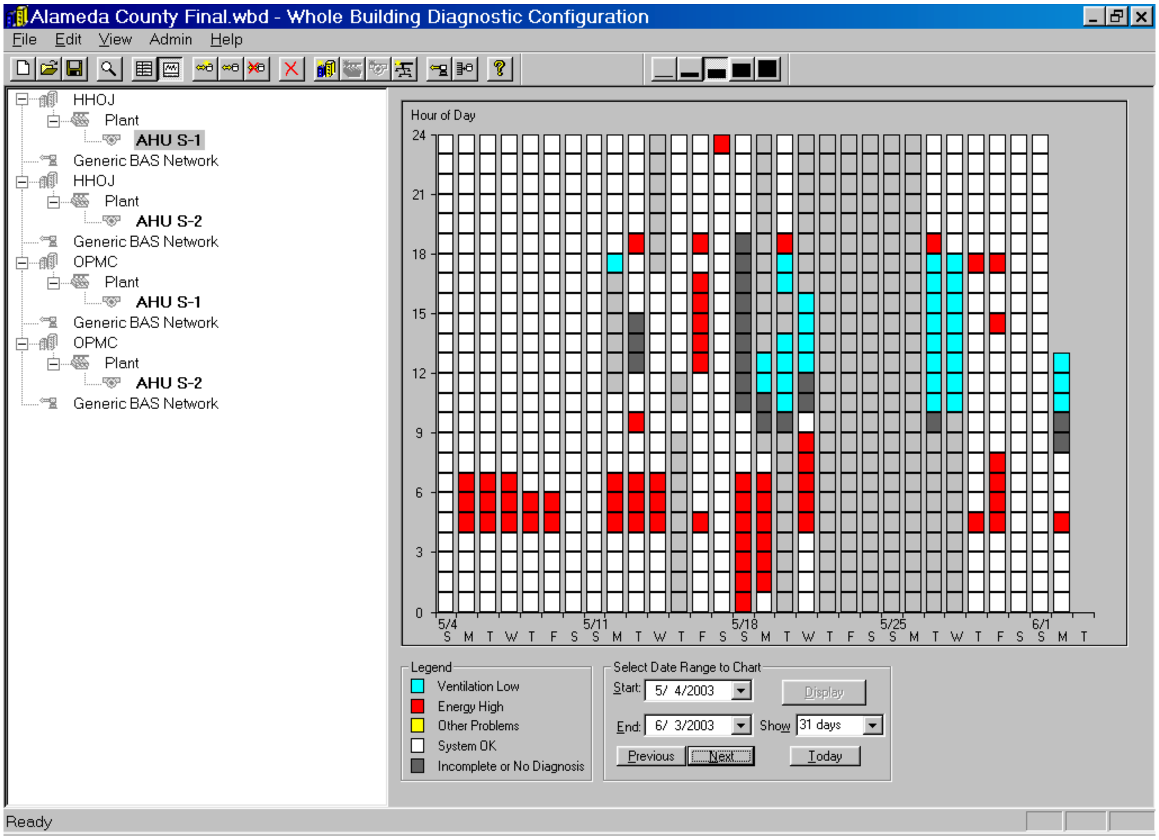

Figure 16 – WBD Online Diagnostic Results for HHOJ AHU-S1 for a Period from May 4, 2003 through June 2, 2003

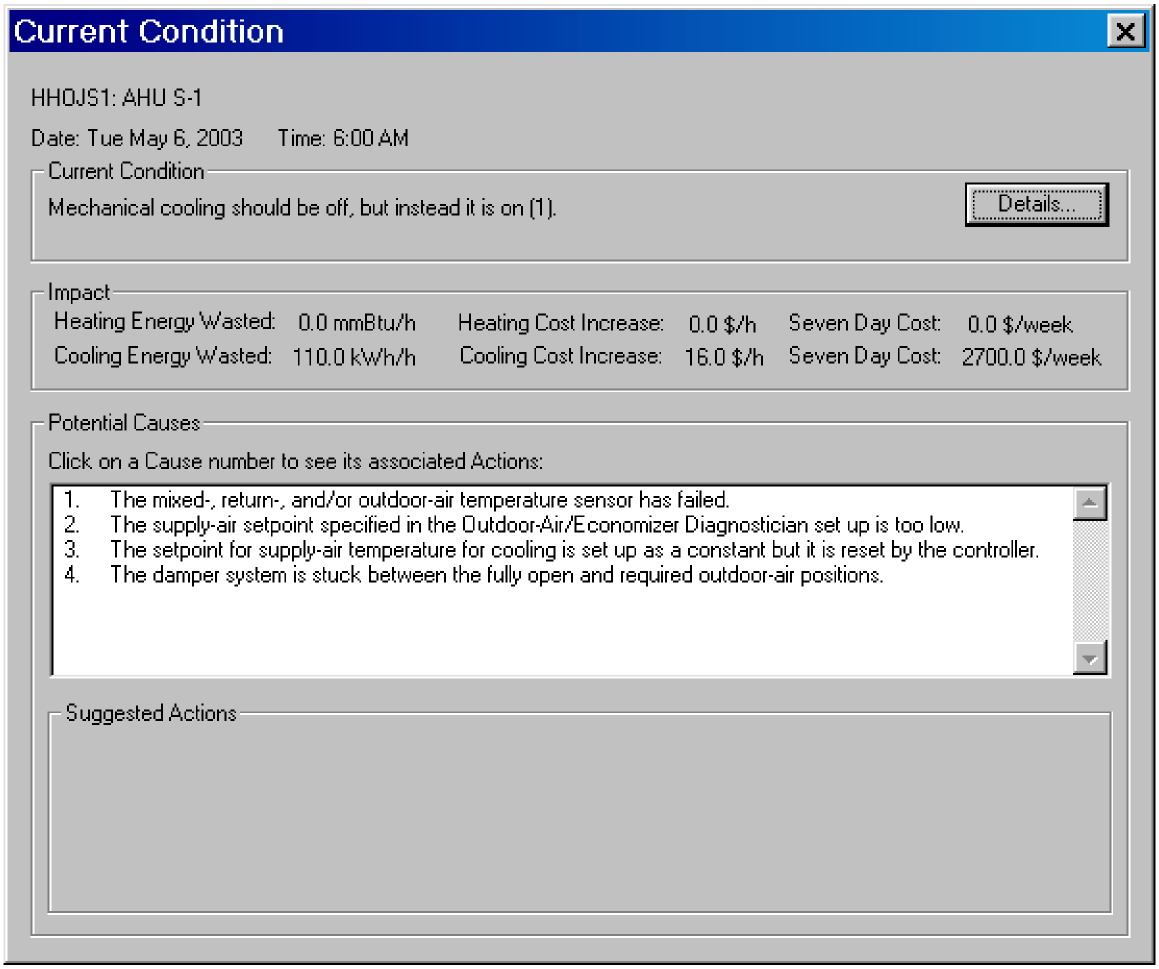

Figure 17 – Current Conditions Dialogue for AHU S-1 Red Cell for May 6, 2003 at 6:00 am

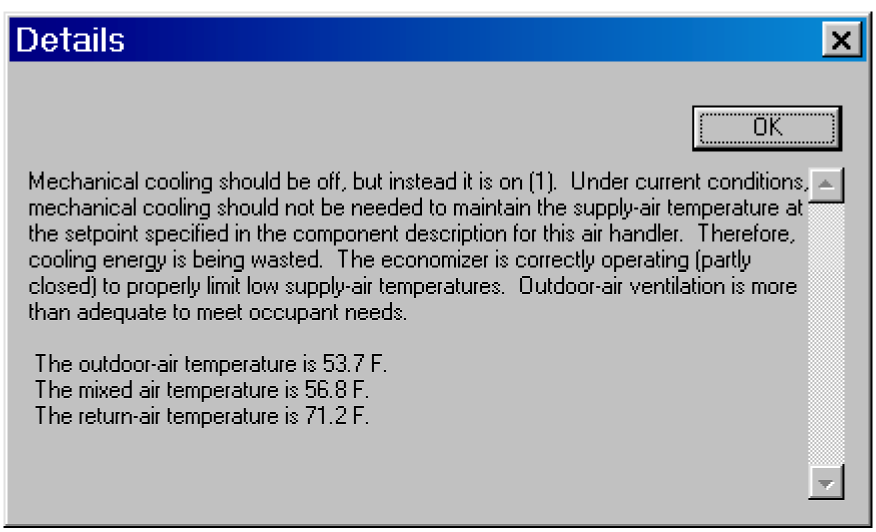

Figure 18 – Details Dialogue for AHU S-1 for May 6, 2003 at 6:00 am

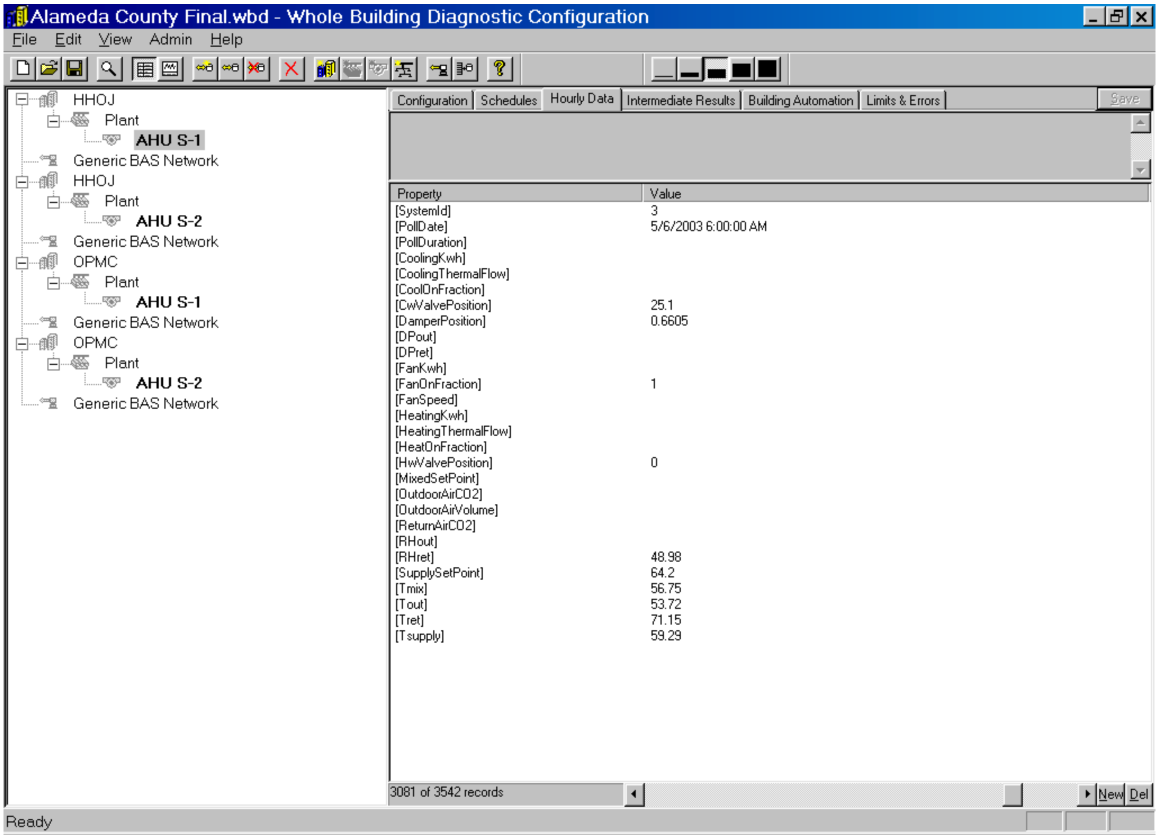

Figure 19 – Hourly Data for AHU S-1 for May 6, 2003 at 6:00 am

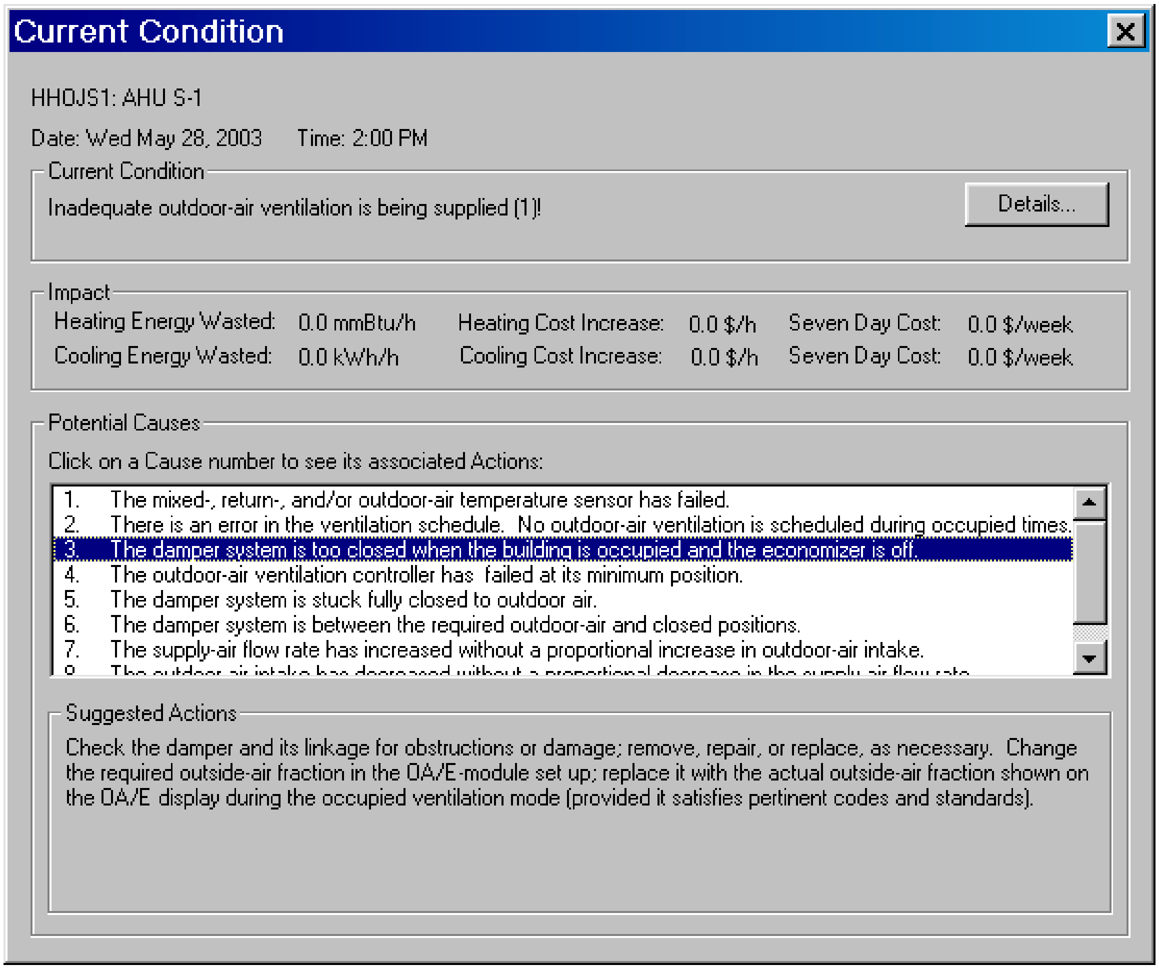

Figure 20 – Current Conditions Dialogue for AHU S-1 Blue Cell for May 28, 2003 at 2:00pm

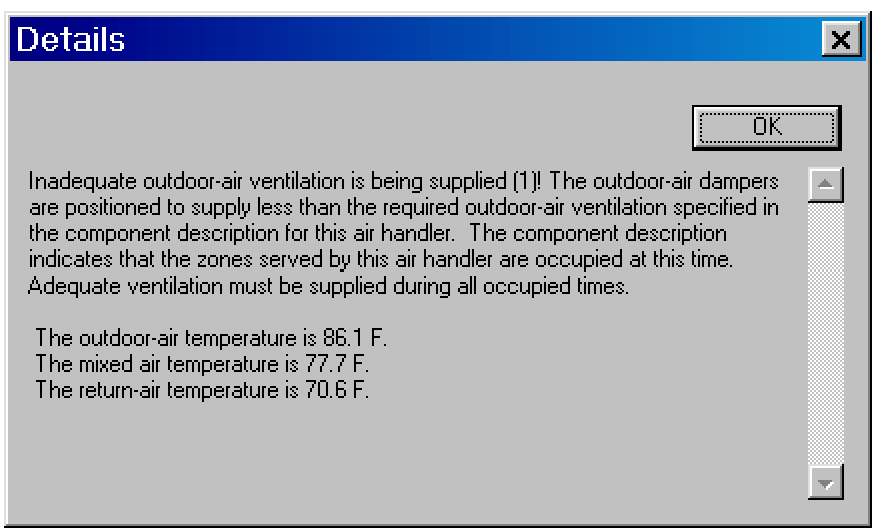

Figure 21 – Details Dialogue for AHU S-1 for May 28, 2003 at 2:00 pm

Table 7 – Frequency of the Problems for HHOJ AHU S-1 when the Supply-Fan was Operational (November 2002 through June 2003)

Category of Operational States	Average Reliability Score	Number of Occurrences	Percent of Total Hours (%)
Control Problem	0.785	2	0.1
Control Problem - Excess Energy	0.950	155	9.5
Excess Ventilation	0.872	52	3.2
Low Economizer Flow	0.934	105	6.4
Inadequate Ventilation	0.918	74	4.5
OK but incomplete	0.856	48	2.9
Operation OK	0.848	1204	73.4
Total		1640	100

8.4 Results for HHOJ AHU S-2

The results from the WBD indicate that like AHU-S1, AHU S-2 is operating improperly as seen from the most current screenshot of the processed results in Figure 22. A significant number of the cells during occupied hours (5 a.m. to 7 a.m.) are red, followed in frequency by blue and gray. The red cells indicating energy waste with the blue and yellow cells, in most cases, indicating a problem with the temperature sensors (outdoor-air, return-air or mixed-air) or low ventilation.

Clicking on one of the red cells (hour 7 a.m. on May 30, 2003) displays the *Current Conditions Dialogue,* shown in Figure 23. The message in the dialogue indicates, "Mechanical cooling should be off but instead is on" and provides a list of potential causes. By browsing the other red cells, this message was found to be common. The problems during this period were found to be the same problems as described with the red cells of AHU S-1 previously. Although the OAE diagnostician has detected a problem, it cannot isolate the exact problem. However, during this occupied period, examination of the OAE hourly data has indicated the cooling valve is 65% open and the outdoor-air damper is in the 65% open position, as shown in Figure 24. For this period the cooling valve should be closed and the damper positioned to meet the (64.7^{o}F) supply-air setpoint. Another item indicated by the OAE hourly data is the mixed-air temperature (56.9^{o}F) is almost equal to the outdoor-door temperature (56.5^{o}F), which indicates the outdoor damper is fully open, although the damper signal is only 65%. Upon further investigation of other red cells and associated hourly data indicates the chilled water valve and economizer damper, at the start of the occupied period (5 a.m.), both start in the 30% position and don't adjust properly until around 7 a.m. This positioning problem of the chilled water valve and damper and the temperature sensor problem were common throughout the demonstration period.

Clicking on one of the blue cells (hour 5:00 pm on May 28, 2003) displays the *Current Conditions Dialogue,* shown in Figure 25. The message in the dialogue indicates, "Inadequate outdoor-air ventilation is being supplied" and provides a list of potential causes. By browsing the other blue cells, this message was found to be common. Clicking on the *Details* button provides additional information on the nature of the problem, as shown in Figure 26. This provides a more detailed description of the problem, and some key data upon which detection of the problem is based. Review of the measured data can also help understand the problem better.

Although the OAE diagnostician has detected a problem with the low ventilation, it cannot isolate the exact problem.

The frequency of problems reported for AHU S-2 is shown in Table 8 (November 2002 through June 2003). The AHU S-2 unit operates at 10% of the occupied period with a control problem, 4% of the time with excess ventilation problem, 3% with inadequate ventilation and 7% with low economizer flow (economizer not fully open).

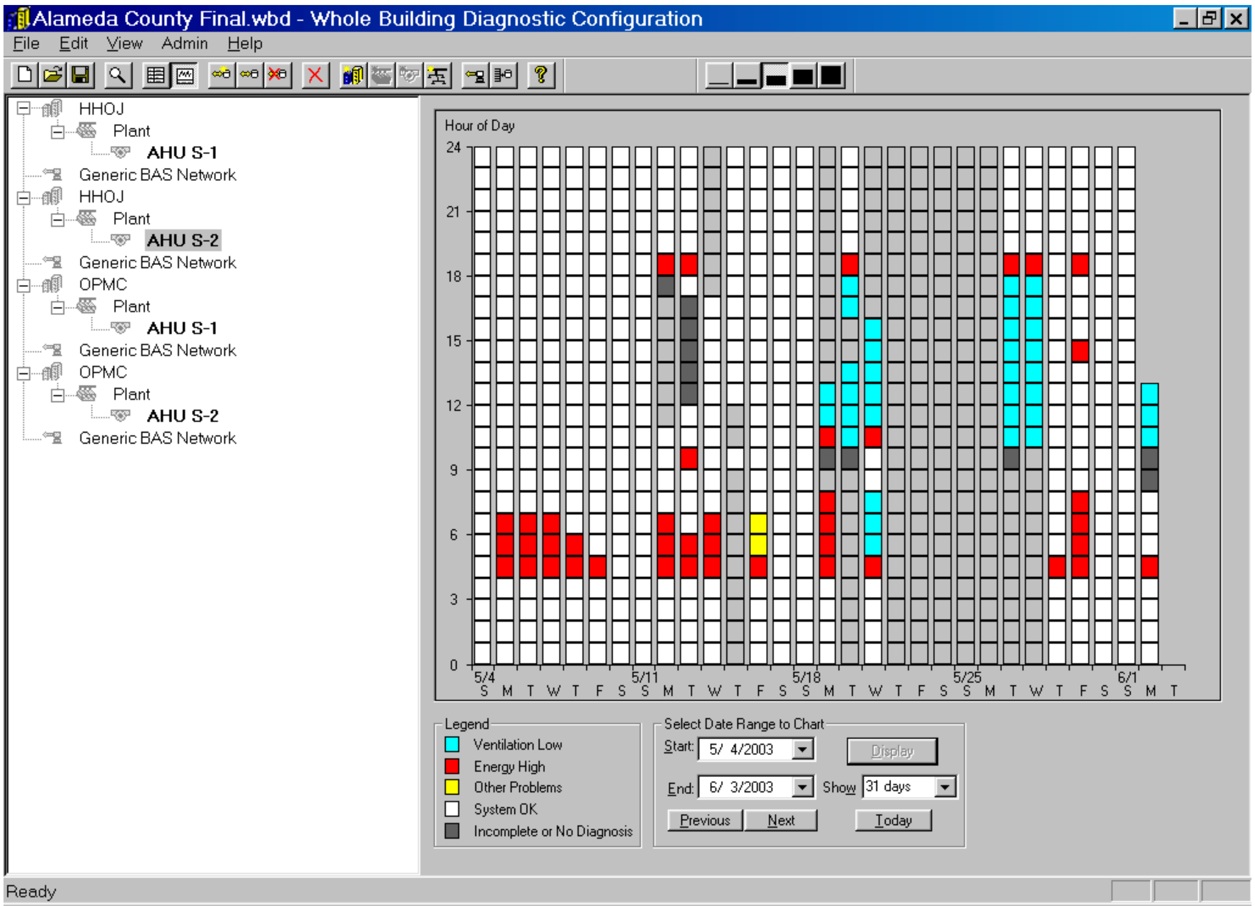

Figure 22 – WBD Online Diagnostic Results for HHOJ AHU-S2 for a Period from May 4, 2003 through June 2, 2003

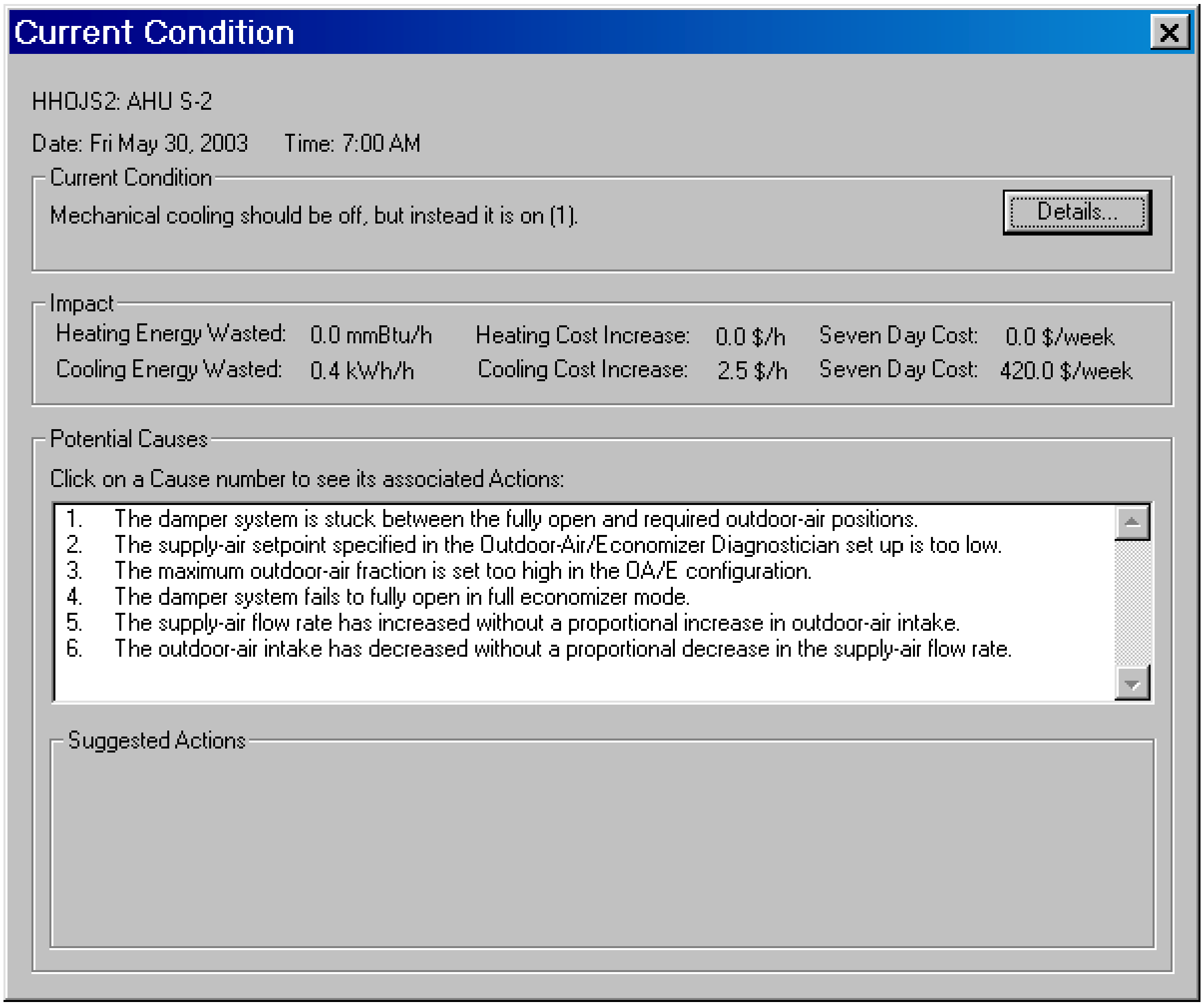

Figure 23 – Current Conditions Dialogue for AHU S-2 Red Cell for May 30, 2003 at 7:00 am

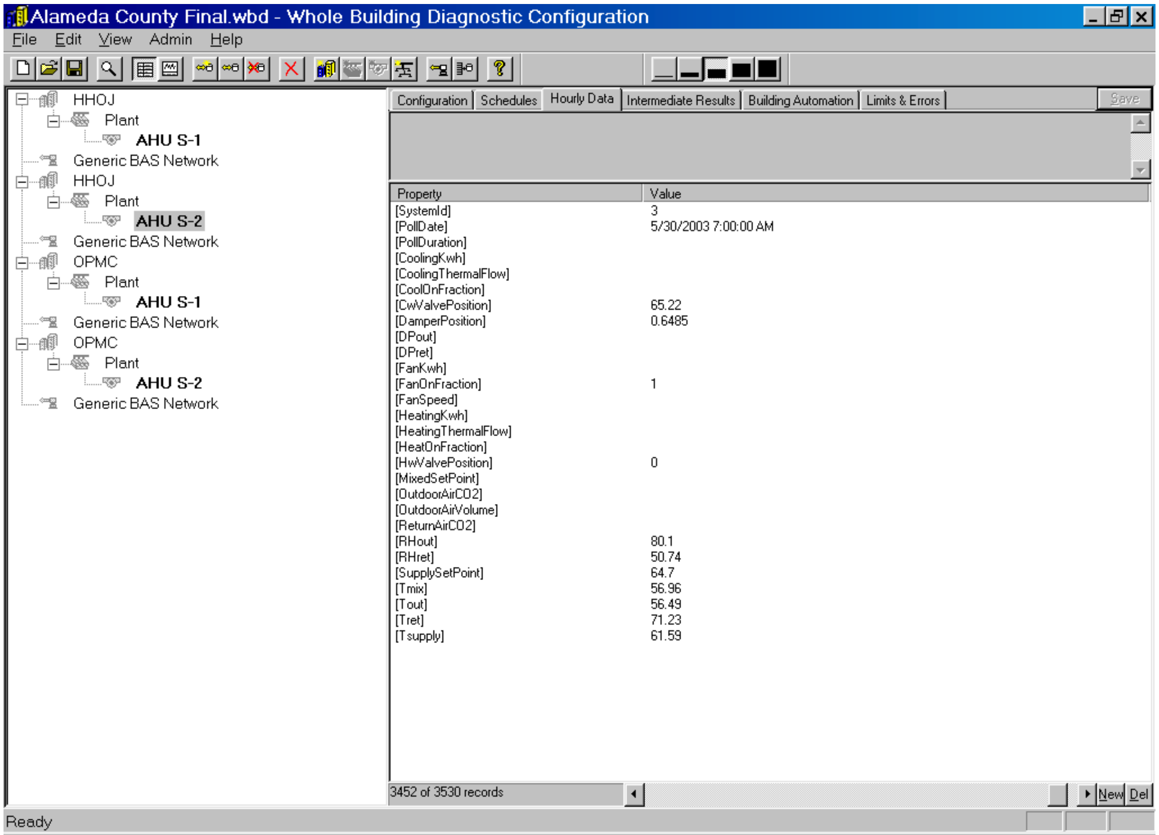

Figure 24 – Hourly Data for AHU S-2 for May 30, 2003 at 7:00 am

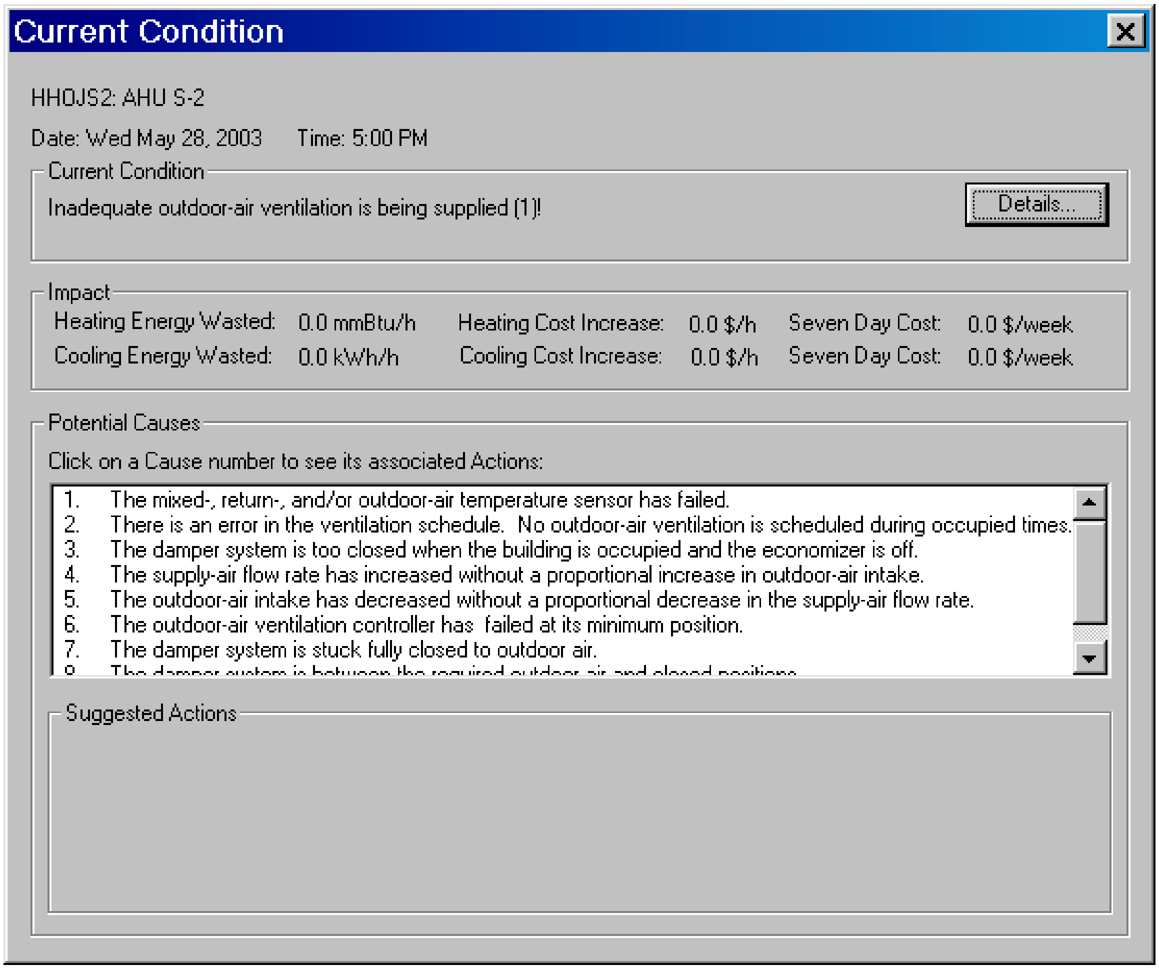

Figure 25 – Current Conditions Dialogue for AHU S-2 Blue Cell for May 28, 2003 at 5:00 pm

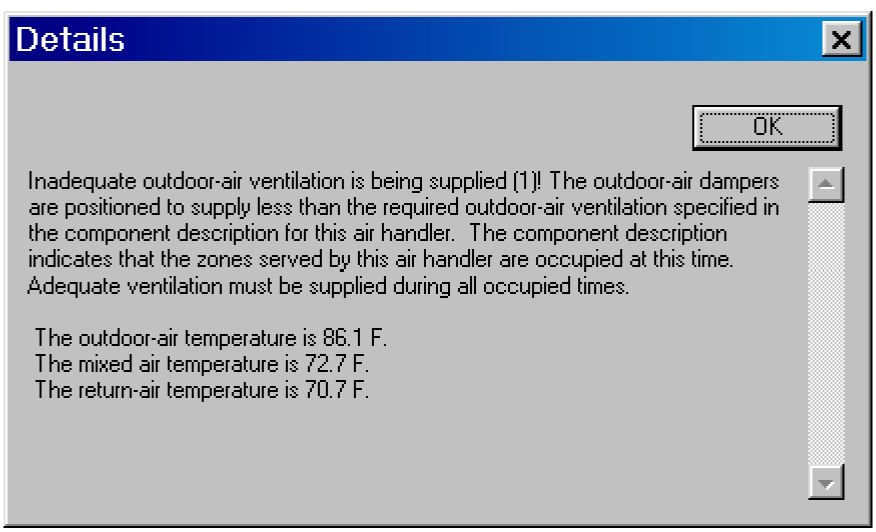

Figure 26 – Details Dialogue for AHU S-1 for May 28, 2003 at 5:00 pm

Table 8 – Frequency of the Problems for HHOJ AHU S-2 when the Supply-Fan was Operational (November 2002 through June 2003)

Category of Operational States	Average Reliability Score	Number of Occurrences	Percent of Total Hours (%)
Control Problem	0.885	18	1.2
Control Problem - Excess Energy	0.947	129	8.3
Excess Ventilation	0.875	65	4.2
Low Economizer Flow	0.936	108	7.0
Inadequate Ventilation	0.888	47	3.0
OK but incomplete	0.845	45	2.9
Operation OK	0.798	1137	73.4
Total		1549	100

8.5 Results for OPMC AHU S-1

The results from the WBD indicate that AHU-S1 is operating improperly as seen from the screenshot of the processed results in Figure 27. A significant number of cells during occupied hours are red, followed in frequency by yellow and blue. The red cells indicating energy waste with the blue and yellow cells, in most cases, indicating a problem with the temperature sensors (outdoor-air, return-air or mixed-air) or low ventilation.

Clicking on one of the red cells (hour 6 on May 6, 2003) displays the *Current Conditions Dialogue,* shown in Figure 28. The message in the dialogue indicates, "Mechanical cooling should be off but instead is on" and provides a list of potential causes. By browsing the other red cells, this message was found to be common. Clicking on the *Details* button provides additional information on the nature of the problem, as shown in Figure 29. The Details dialogue indicates the outdoor-air temperature reading is (57^{o}F), mixed-air temperature (58.9^{o}F) and a return-air temperature of (72.1^{o}F). It also provides a more detailed description of the problem, and some key data upon which detection of the problem is based. Review of the measured data can also help understand the problem better. In this case, the mixed-air temperature (58.9^{o}F) would indicate it should be sufficiently low enough to cool without requiring mechanical cooling. Although the OAE diagnostician has detected a problem, it cannot isolate the exact problem. However, during this occupied period, examination of the OAE hourly data has indicated the cooling valve is 99% open and the outdoor-air damper is in the 100% open position, as shown in Figure 30. During this period the cooling valve should be closed and the damper positioned to meet the (60.5^{o}F) supply-air set point.

Another problem indicated, as displayed in the *Current Conditions Dialogue* after clicking on other red cells, "The economizer should be fully open, but is only partially open". This diagnostic was common throughout the demonstration period and was associated with the cooling valve being open and economizer only being partially open when the outdoor air was cool enough to cool the space without mechanical cooling or could assist with the mechanical cooling. As a result, cooling energy is being wasted because additional cool outdoor air could be used to replace some mechanical cooling. Other problems, indicated by the yellow cells, were diagnosed throughout the demonstration period with a majority of them associated with temperature sensor problems.

Clicking on one of the blue cells (hour 6:00 p.m. on March 14, 2003) displays the *Current Conditions Dialogue,* shown in Figure 31. The message in the dialogue indicates, "No outdoor-air is being supplied" with no potential causes given at this time. By browsing the other blue cells, this message was found to be common. Clicking on the *Details* button provides additional information on the nature of the problem, as shown in Figure 32. This provides a more detailed description of the problem, and some key data upon which detection of the problem is based. Review of the measured data can also help understand the problem better. Although the OAE diagnostician has detected a problem with no outdoor-air is being supplied and the supply fan is off, it cannot isolate the exact problem. In this case further review of hourly data has indicated the supply fan is off and the occupancy schedule most likely has changed and the WBD configuration has not been updated.

The frequency of problems reported for OPMC AHU S-1 is shown in Table 9 (February 2001 through June 2003). AHU S-1 operates at 24% of the occupied period with a control problem, 7% of the time with excess ventilation problem, 2% with inadequate ventilation and 13% with low economizer flow (economizer not fully open).

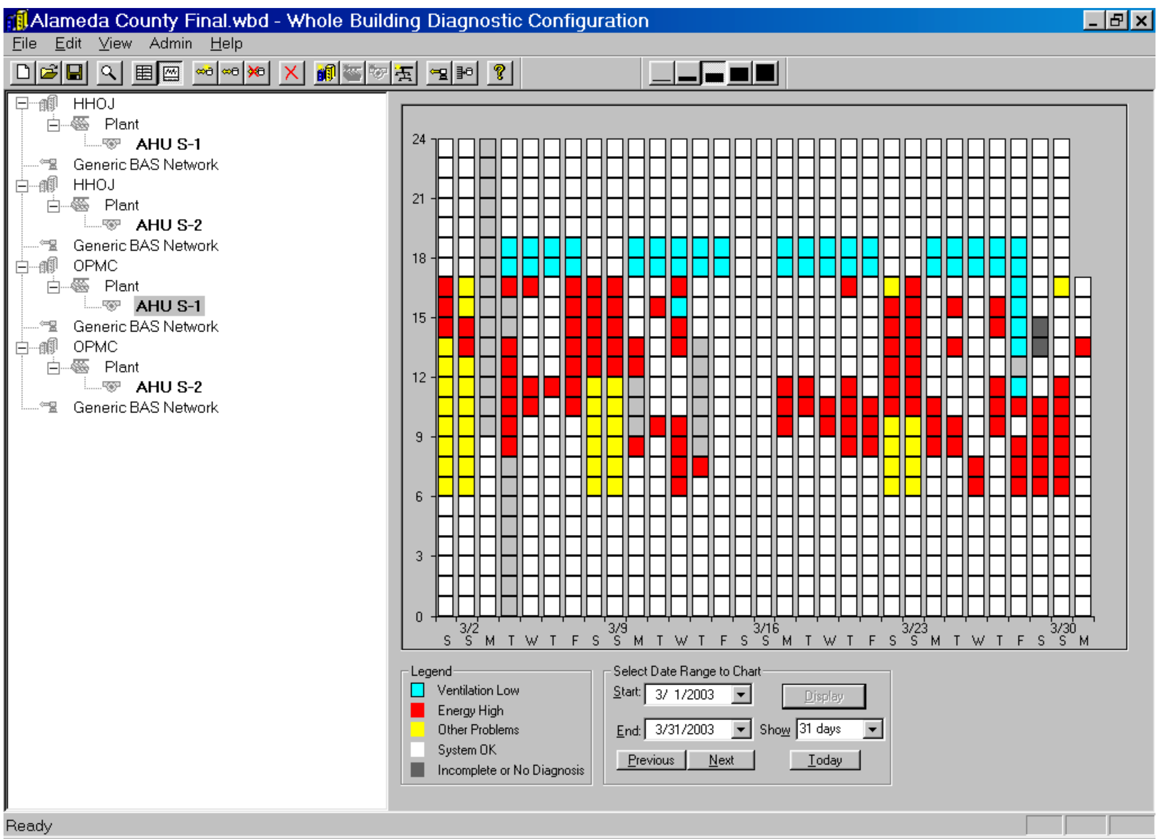

Figure 27 – WBD Online Diagnostic Results for OPMC AHU-S1 for a Period from March 1, 2003 through March 31, 2003

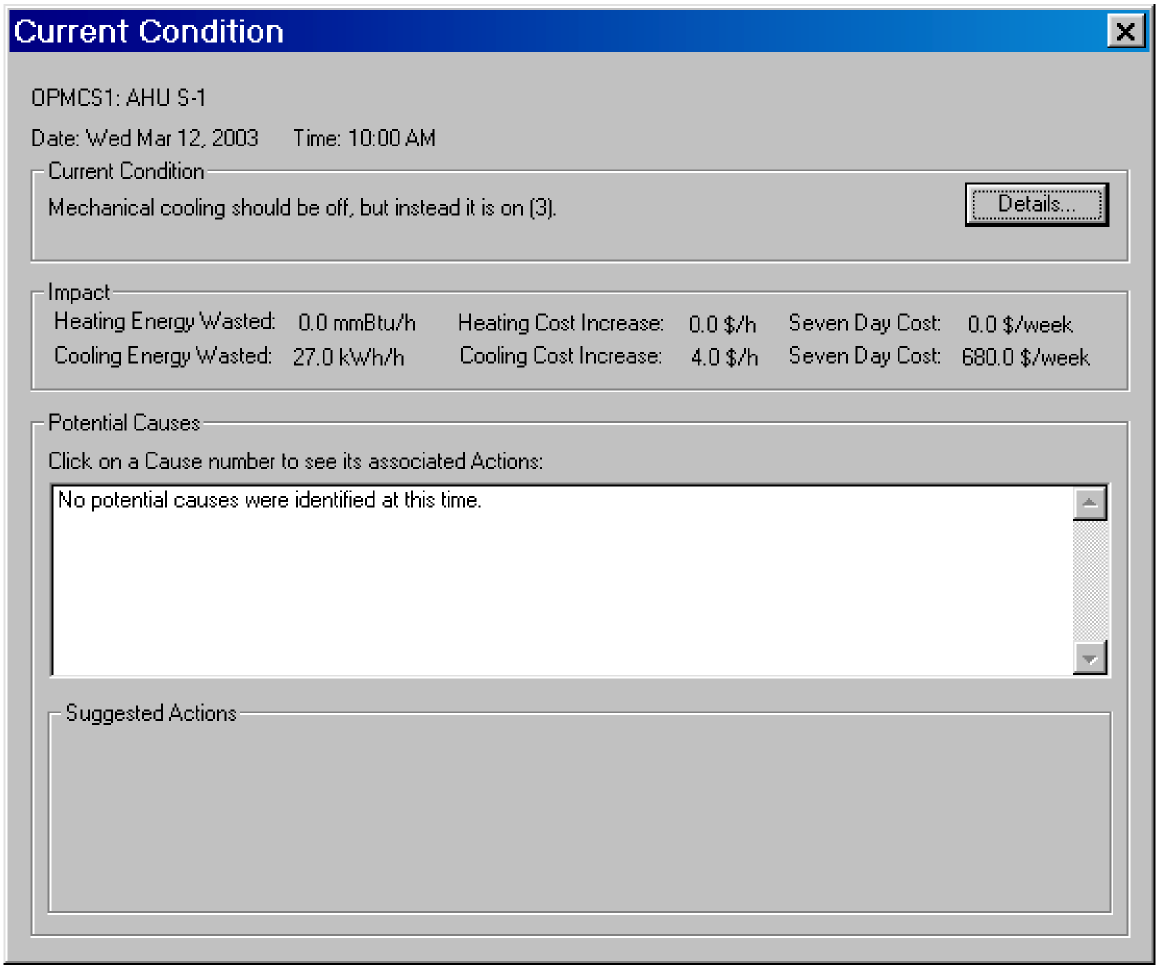

Figure 28 – Current Conditions Dialogue for AHU S-1 Red Cell for March 12, 2003 at 10:00am

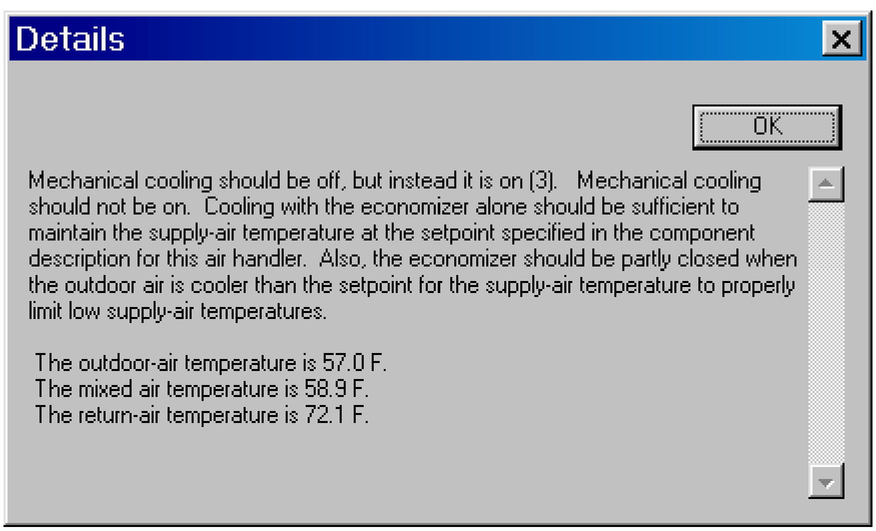

Figure 29 – Details Dialogue for AHU S-1 for March 12, 2003 at 10:00 am

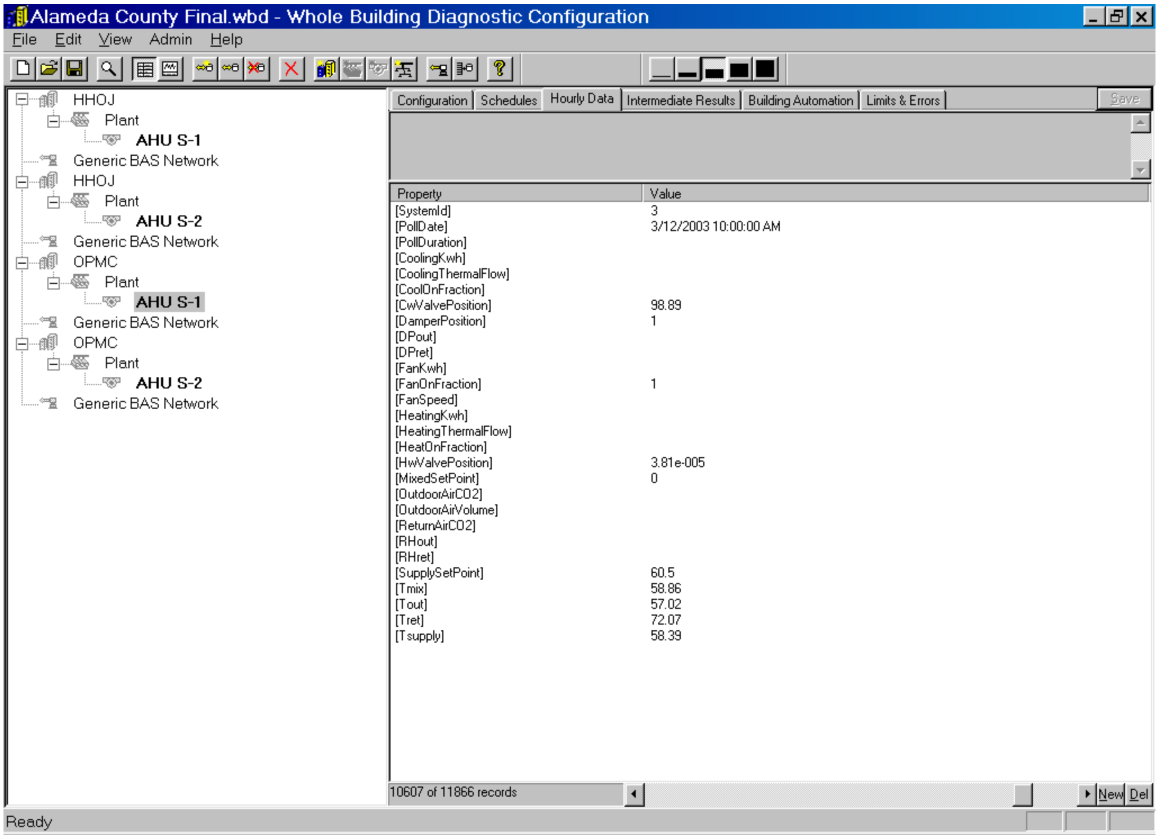

Figure 30 – Hourly Data for AHU S-1 for March 12, 2003 at 10:00 am

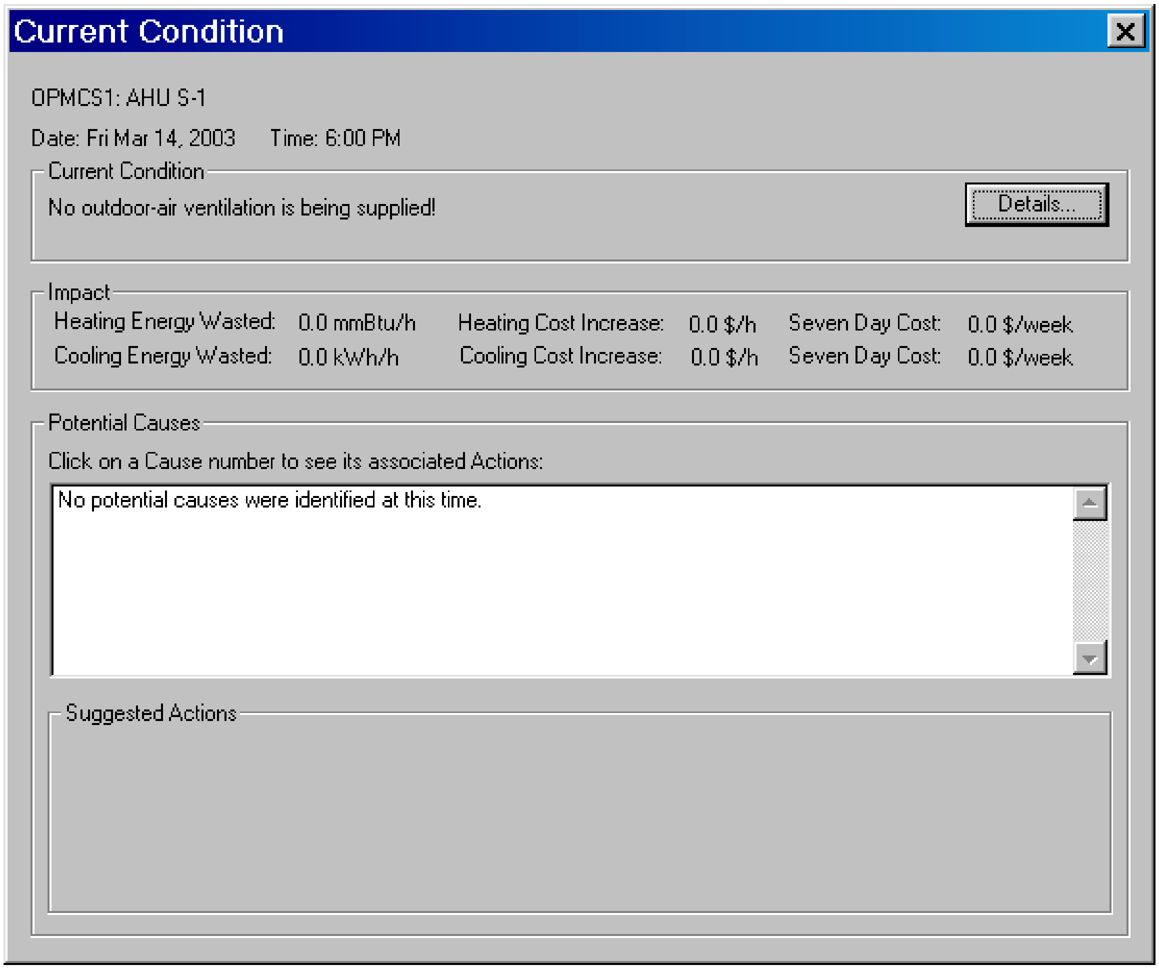

Figure 31 – Current Conditions Dialogue for AHU S-1 Blue Cell for March 14, 2003 at 6:00 pm

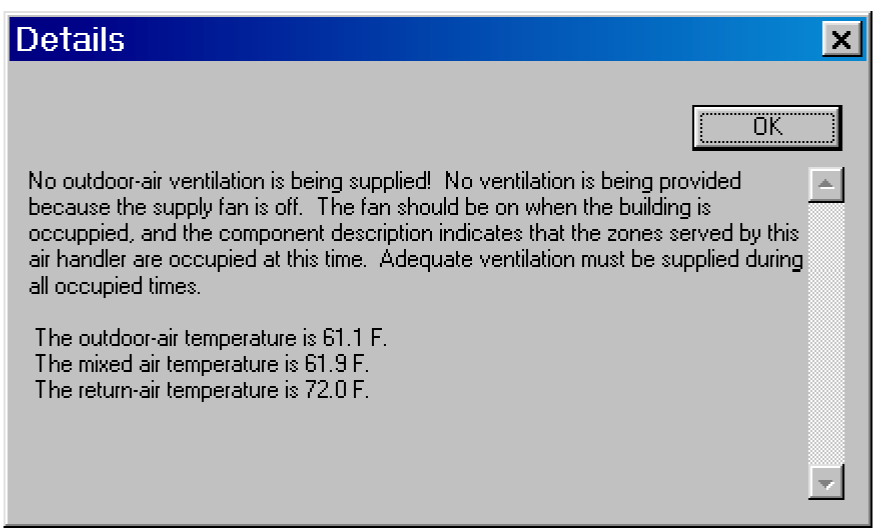

Figure 32 – Details Dialogue for AHU S-1 for March 14, 2003 at 6:00 pm

Table 9 – Frequency of the Problems for OPMC AHU S-1 when the Supply-Fan was Operational (February 2001 through June 2003)

Category of Operational States	Average Reliability Score	Number of Occurrences	Percent of Total Hours (%)
Control Problem	0.776	426	6.3
Control Problem - Excess Energy	0.911	1197	17.7
Excess Ventilation	0.931	471	6.9
Low Economizer Flow	0.875	851	12.6
Inadequate Ventilation	0.910	143	2.1
OK but incomplete	0.960	1047	15.5
Operation OK	0.729	2635	38.9
Total		6770	100

8.6 Results for OPMC AHU S-2

The results from the WBD indicate that AHU-S2 is operating improperly as seen from the screenshot of the processed results in Figure 33. A number of cells during occupied hours are red, followed in frequency by blue. The red cells indicating energy waste with the blue cells, in most cases, indicating a problem with the temperature sensors (outdoor-air, return-air or mixed-air) or low ventilation.

Clicking on one of the red cells (hour 2 p.m. on March 12, 2003) displays the *Current Conditions Dialogue,* shown in Figure 34. The dialogue indicates, "The economizer should be fully open, but is only partially open" and provides a list of potential causes. In this case no potential causes were identified. By browsing the other red cells, this message was found to be common. Clicking on the *Details* button provides additional information on the nature of the problem, as shown in Figure 35. The Details dialogue indicates the outdoor-air temperature reading is 68°F, mixed-air temperature 67.1°F and a return-air temperature of 71.4°F. It also provides a more detailed description of the problem, and some key data upon which detection of the problem is based. Review of the measured data can also help understand the problem better. Although the OAE diagnostician has detected a problem, it cannot isolate the exact problem. However, during this occupied period, examination of the OAE hourly data has indicated the cooling valve is 27% open and the outdoor-air damper is in the 73% open position, as shown in Figure 36. During this period the damper should be positioned at 100% to allow the cooler outdoor air to replace the warmer return air.

Another problem indicated, as displayed in the *Current Conditions Dialogue* after clicking on other red cells, "Mechanical cooling should be off but instead is on." This diagnostic was common throughout the demonstration period and was associated with the cooling valve being open when cooling with the economizer alone should be sufficient to maintain the supply-air temperature at the setpoint specified in the component description for this air handler. As a result, cooling energy is being wasted because cool outdoor air could be used in place of mechanical cooling.

Clicking on the blue cells, during the demonstration, displays the *Current Conditions Dialogue*. The dialogue indicates, "Inadequate outdoor-air ventilation is being supplied" or "No outdoor-air ventilation is being supplied" and was found to be common throughout this period. Although the OAE diagnostician has detected a problem with inadequate outdoor-air ventilation and no outdoor-air ventilation being supplied, it cannot isolate the exact problem. In this case, further review of hourly data has indicated the supply fan is off and the occupancy schedule most likely has changed and the WBD configuration has not been updated.

The frequency of problems reported for OPMC AHU S-2 is shown in Table 10 (May 2001 through June 2003). The AHU S-2 unit operates at less than 19% of the occupied period with a control problem, 2% of the time with excess ventilation problem, 1% with inadequate ventilation and 12% with low economizer flow (economizer not fully open).

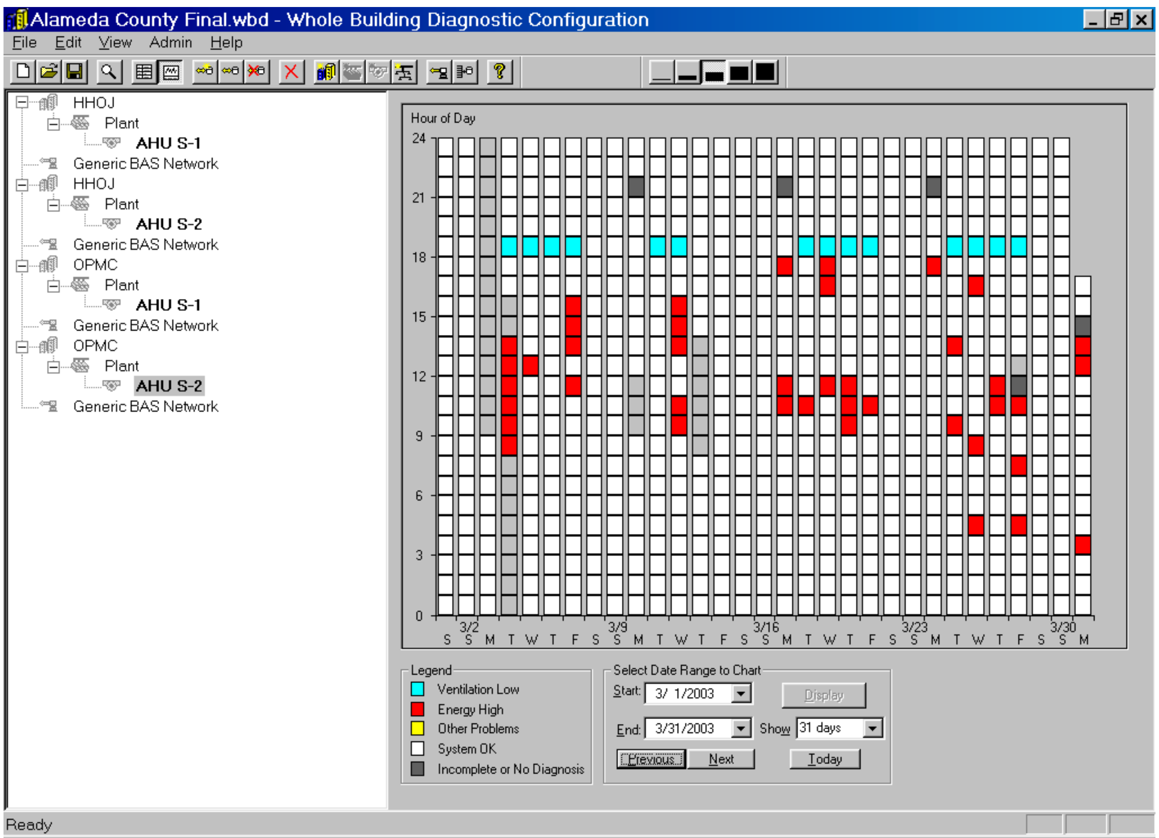

Figure 33 – WBD Online Diagnostic Results for OPMC AHU-S2 for a Period from March 1, 2003 through March 31, 2003

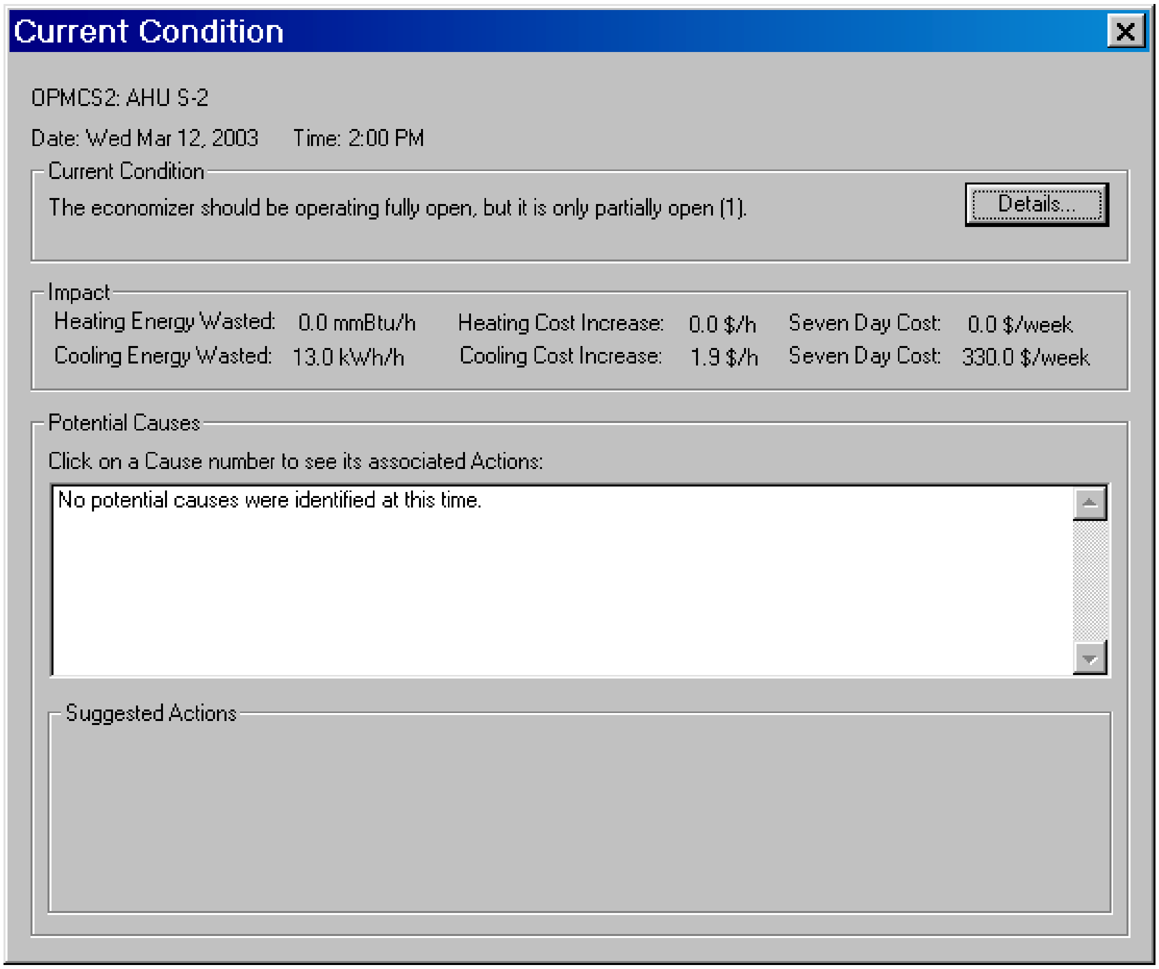

Figure 34 – Current Conditions Dialogue for AHU S-2 Red Cell for March 12, 2003 at 2:00 pm

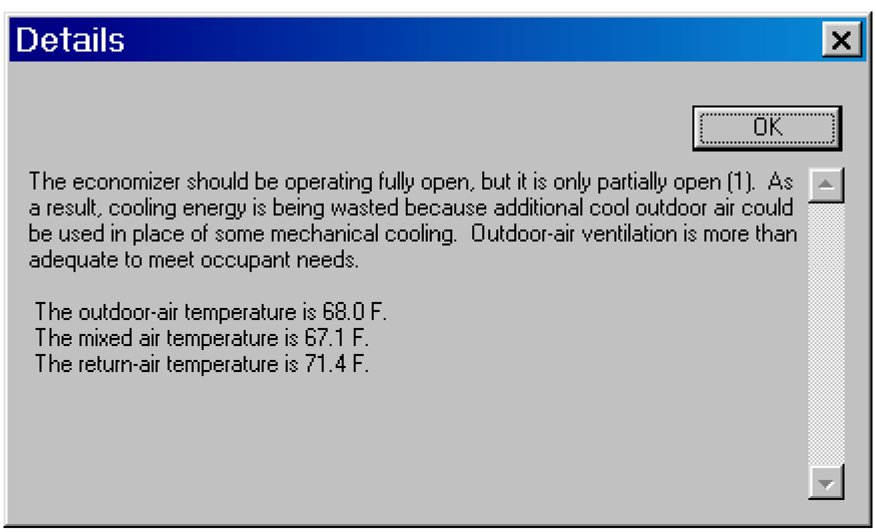

Figure 35 – Details Dialogue for AHU S-2 for March 12, 2003 at 2:00 pm

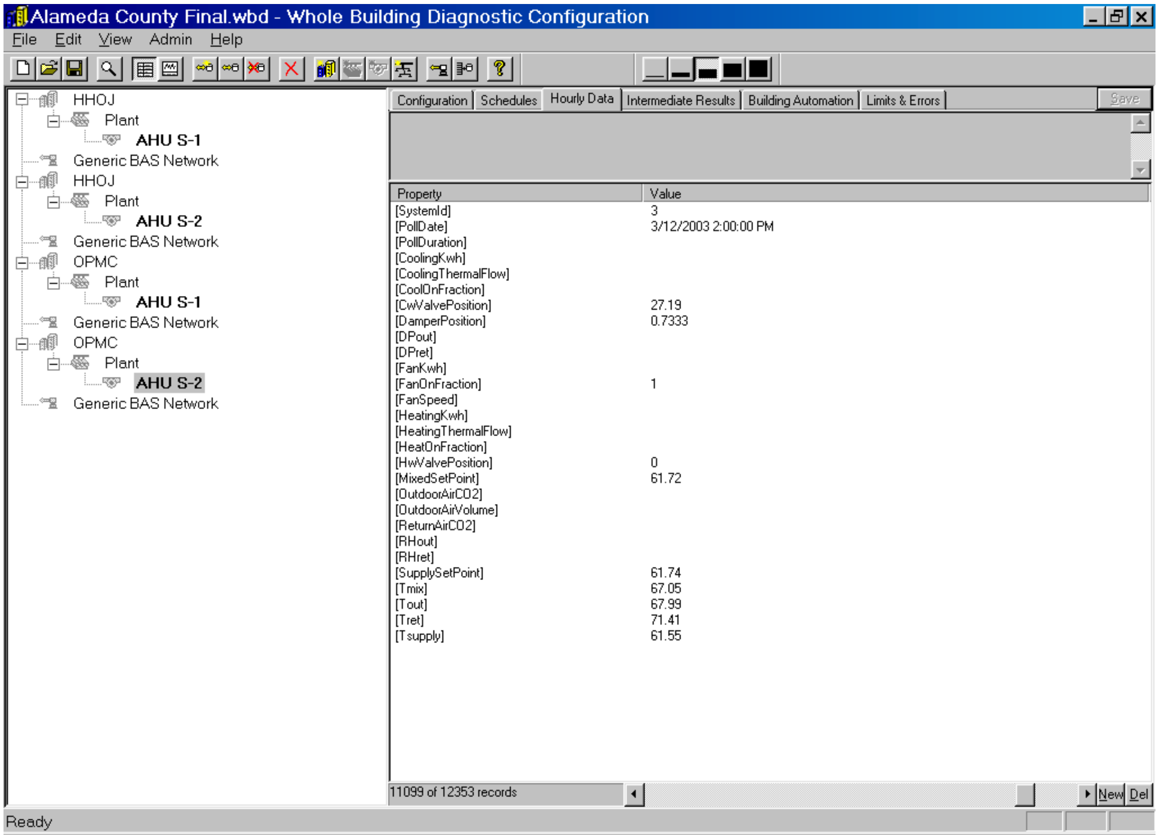

Figure 36 – Hourly Data for AHU S-2 for March 12, 2003 at 2:00 pm

Table 10 – Frequency of the Problems for OPMC AHU S-2 when the Supply-Fan was Operational (May 2001 through June 2003)

Category of Operational States	Average Reliability Score	Number of Occurrences	Percent of Total Hours (%)
Control Problem	0.902	38	0.7
Control Problem - Excess Energy	0.898	989	18.4
Excess Ventilation	0.910	89	1.7
Low Economizer Flow	0.876	663	12.3
Inadequate Ventilation	0.954	64	1.2
OK but incomplete	0.807	264	4.9
Operation OK	0.770	3270	60.8
Total		5377	100

8.7 Saving Opportunities

Correcting the energy-wasting problems identified by OAE will produce reductions in energy consumption and savings on energy expenditures at Alameda County. In this section, we present the savings estimated by the OAE diagnostician from correcting the problems for all four AHU's.

A summary of problems identified and energy savings impact estimated by the OAE diagnostician are listed in Table 12. All four AHU's have problems that are related to improper operations of the outdoor-air damper. In addition, there are sporadic problems associated with ventilation during certain time. The building operator has confirmed all problems, but none of them have been corrected yet.

When the OAE diagnostician identifies improper operation at any given hour, it also estimates the heating or cooling energy impact by comparing the actual operation to the expected operation. Energy and cost impacts are not estimated if a temperature sensor problem exists or if the ventilation rate is inadequate. The impact estimates are based on both the measured data and user-specified inputs [e.g., the system coefficient of performance (COP) and cost of energy]. Because measured values are used in estimating the impacts, the sensors must be fault free. If the AHU has a faulty sensor (especially, the outdoor-air, return-air or mixed-air temperature), the estimates are not accurate and cannot be relied upon. After estimating the energy impact, the OAE then estimates the cost impacts using the user specified energy conversion efficiency for the heating or the cooling systems and cost of the energy. The heating and cooling system (including all auxiliary systems) efficiency and energy costs (blend cost that includes demand charges as well) are listed in Table 11.

Table 11 – Heating and Cooling System Efficiency and Energy Costs

	Heating	Cooling
Efficiency	80%	2.5 COP
Cost	6$/mmBtu	0.15$/kWh

All four AHU's at Alameda County are VAV systems. Although OAE can detect problems with VAV systems, the energy and cost impacts are based on the design load flow rate (or full load flow rate). Because the airflow rate in a VAV system modulates to match the load, the energy and cost impacts estimated with design flow rate are probably overestimated. A typical average fan speed (speed is proportional to air flow rate) during occupied hours in a high-rise office building with a VAV system is around 80% (Katipamula et a. 2003). Therefore, the estimated impacts are overestimated by about 20%.

The energy cost impact for the six AHU's ranged from $300 (six moths) to $15,000 (18 months). Although the results from HHOJ cannot be scaled directly to an annual basis because they are highly depended on both indoor and outdoor conditions, the annual impacts will be significantly higher than the impacts reported in Table 12.

Table 12 – Summary of Problems and Cost Impact at Alameda County

AHU	Problem Detected	Number of Hours	Problem Confirmed	Problem Corrected	Energy Cost Impact ($)
HHOJ AHU S-1	Outdoor-air damper problem – not economizing fully	4,033	Yes	No	1,800
HHOJ AHU S-2	Outdoor-air damper problem – not economizing fully	4,033	Yes	No	300
OPMC AHU S-1	Outdoor-air damper problem – not economizing fully	12,092	Yes	No	15,750
OPMC AHU S-2	Outdoor-air damper problem – not economizing fully	12,577	Yes	No	10,000
				Total Site Cost Impact	**27,850**

Although it is difficult to estimate annual savings at Alameda County the projected annual energy savings from correcting all problems at Alameda County will be in the range of $10,000 to $16,000. As stated earlier, these savings are probably overstated because the supply fan operation was assumed to constant. On the other hand, other operation problems may have been present in the AHU's, but the presence of the problem found may have masked these other problems. Before the *single-fault* nature of the logic implemented in the OAE, it only identified one prominent fault at a time. As a result, addition opportunities to improve the performance of AHU's may be available, as well as the associated savings. The OAE will reveal other problems after the one identified here is corrected.

9 User Impressions of the WBD

An exit interview was conducted with Mr. Don Lucas, the WBD site administrator for Alameda County, in July 2003. The results of that interview and his general comments are presented and summarized in this section.

9.1 General

Mr. Lucas thought the WBD diagnostic tool set helped him in evaluating trends and identifying operational issues related to the AHU's at both the Hayward Hall of Justice and the Alameda County Courthouse. In addition, he thought that diagnostic tools such as WBD would help building managers and operators by providing them with the ability to evaluate real-time data and the ability to provide corrective actions. He liked the tools ability to indicate energy savings and in identifying problems, with possible solutions, so the building operators could save time in tracking down problems. He also expressed interest in expanding the demonstration to the other AHU systems in the County. He also noted his staff currently spends almost 40 hours a month diagnosing and chasing problems.

9.2 OAE Interface and Diagnostics

On a scale of 1 to 5 (1 being very easy and 5 being very difficult to use) Mr. Lucas gave the WBD a rating of 1, on ease of use. He indicated building managers and operators need an automated tool like the OAE module to detect and diagnose problems. He indicated that the configuration of the diagnostician was somewhat difficult and required a lot of detailed information about the system. He also indicated he would continue to use the WBD/OAE beyond the demonstration period.

Mr. Lucas indicated that he reviewed results on a daily basis and confirmed an inoperable damper linkage problem with the building operator. Although this was the only problem corrected, none of the other problems identified were corrected. When asked if he would install additional sensors if that allowed for better diagnosis of problems, he indicated that he would. When asked about recommendations for changes or improvements to the OAE/WBD, Mr. Lucas indicated the tools were fine and did not need any improvements with the exception of data collection. When asked what other tools he would like to see incorporated into the WBD he indicated, boiler, chiller and cooling tower systems.

There was only one negative feedback expressed by Mr. Lucas and that was the difficulty encountered with data collection.

10 Conclusions and Recommendations

The WBD OAE module was shown to successfully identify a number of major problems with the AHU's at Alameda County. These findings are consistent with other demonstrations of the WBD, where OAE found similar problems that should have been detected at the time of commissioning or periodic maintenance.

The OAE diagnostic module identified problems with all four AHU's at the demonstration site. Based on the results, we recommend a few corrective actions for the Alameda County air handlers:

- Modify the damper controls on HHOJ AHU S-1 so that the damper is fully open during economizing operations; the current operations are improper and is costing the building over **$1,800** for the six month monitoring period

- Modify the damper controls on HHOJ AHU S-2 so that the damper is fully open during economizing operations; the current operations are improper and is costing the building over **$300** for the six month monitoring period

- Modify the damper controls on OPMC AHU S-1 so that the damper is fully open during economizing operations; the current operations are improper and is costing the building over **$15,000** for the 18 month monitoring period

- Modify the damper controls on OPMC AHU S-2 so that the damper is fully open during economizing operations; the current operations are improper and is costing the building over **$10,000** for the 18 month monitoring period

Installation of the WBD and collection of data from the air handlers were not smooth because of various reasons at this site. A modified automated process had to be developed after the start of the project, which cost us valuable demonstration time.

The demonstration reinforced the notion that diagnostic tools produce savings only when the identified problems are fixed. Merely identifying operation problems and their impacts is not sufficient by itself; building staff must fix them. If building staffs are not able to use their control systems to correct problems, are too busy with other duties, or lack resources to obtain help from contractors, savings will not be realized. A delivery mechanism is needed that helps ensure that building staff takes action when alerted to problems with significant impacts.

The time and cost of diagnostic-tool installation is a significant component to implementing diagnostic technologies. Labor costs to set up tools like the WBD (~1 week) will likely exceed the purchase cost of commercialized software. Sites with larger air handlers (10,000 cfm or larger air flow rates) have greater savings per problem fixed, while installation costs do not vary with air handler size (i.e., savings are greater relative to costs). Installation costs per air-handler also go down as the number of air handlers at a site increases, provided the units use similar operating control strategies and are part of the same underlying control system.

Overall, the WBD OAE diagnostician was successfully applied at Alameda County. It identified problems with significant energy and cost penalties that would provide significant savings if fixed. Getting building staff to correct these problems, however, was difficult. This points to a need to develop a mechanism for delivering the OAE or providing its results to users in a way that better encourages them to correct the problems found.

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Task Report for the

Energy Efficient and Affordable Small Commercial and Residential Buildings Research Program

a Public Interest Energy Research Program
sponsored by the California Energy Commission

Project 2.4 – Demonstration of the Whole-Building Diagnostician

Task 2.4.15 – Service Provider Demonstration – On-line Test

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August 1, 2003

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1 Executive Summary

This report on Task 2.4.15 – Online Test for the Service Provider Demonstration for Project 2.4 – Demonstration of the Whole-Building Diagnostician, documents the online analysis of data for the service-provider demonstration conducted at the 300 Capitol Mall building in Sacramento. Battelle working with Newport Design Consultants (NDC) implemented the online test configuration, data collection, data analysis, and documentation for this demonstration.

The online test was designed to assess the usability, usefulness, and value of the Whole-Building Diagnostician for providers of HVAC services, in this case by Marina Mechanical. It was also to evaluate the Outdoor-Air Economizer (OAE) diagnostic module's capabilities to automatically and continually diagnose operational problems with air-handling units (AHUs). As part of this online demonstration all six AHUs at 300 Capitol Mall were monitored. The measured data that were collected on a continuous basis included: 1) outdoor-air temperature, 2) return-air temperature, 3) mixed-air temperature, 4) supply-air temperature, 5) chilled-water valve position, 6) supply-fan status, 7) hot-water valve position, 8) supply-air set point, and 9) economizer damper position.

The air handler's control strategy for the outdoor-air and economizer, and the schedule (times of day and days of week) for which the minimum outdoor air must be supplied for the occupants was entered into the WBD's configuration for the air handler. This information was largely obtained from Dave Maron, of BayPoint Controls a division of Marina Mechanical, and the building automation system (BAS) at Capitol Mall; some items were ascertained by observation of the raw data delivered, as is typical in most WBD installations.

For online tests, the data from the AHUs was automatically collected using trend logs and logged into the diagnostician's database using a data collection module, which is also part of the Whole Building Diagnostician (WBD). Although the data requests can be made at any frequency, at Capitol Mall, the data was requested at 5-minute intervals and integrated over the hour before being processed by the OAE diagnostic module. The online data collection process started in September of 2002 for all six AHUs. The data collection process worked well when all parts of the software were up and running. Although several weeks of data were lost, data was obtained for more than six months for all six AHUs.

All six AHUs at Capitol Mall had outstanding problems. The predominant problems for each of the six AHUs are: 1) AHU-1 had the damper not fully opening during economizer operations, 2) AHU-2 had the damper not fully opening during economizer operations and excess ventilation during the heating mode, 3) AHU-3 had the damper not fully opening during economizer operations and excess ventilation during the heating mode, 4) AHU-4 had the damper not fully opening during economizer operations, 5) AHU-5 had the damper not fully opening during economizer operations and excess ventilation during the heating mode, and 6) AHU-6 had excess ventilation during the heating mode.

Mr. Maron the DDC controls service provider and WBD site Administrator, indicated that the WBD diagnostic tool was quite comprehensive and would provide building managers, operators, and owners with the ability to evaluate real-time data and perform corrective measures as required. Mr. Maron indicated that the user interface for both the WBD and the OAE diagnostician was difficult to use. Although the problems identified by the OAE diagnostician were confirmed at the site by Mr. Maron, none of the problems were corrected (see Section 8 for more details on why the problems were not corrected). In addition, the building operators were given a presentation of the WBD but none of them actually reviewed the results during the demonstration. This may be a critical missing link in the process of using such tools and needs further investigation in future applications.

The OAE diagnostician was shown to successfully identify problems with all six AHUs at Capitol Mall. These findings are consistent with the other field demonstrations of the WBD, where the OAE found similar problems that should have been detected at the time of commissioning. The demonstration showed that diagnostic technology is only as good as the fixes to the problems it identifies. That is, it is insufficient to merely identify problems and their impacts and expect operators will fix them as a result. If users are not proficient in using their control systems to correct problems, are too busy with other duties, or lack resources to obtain help from contractors, diagnostic technologies alone will not result in system efficiency improvements. Improvements can only be realized in buildings where identified problems are corrected. Future demonstrations or broad deployment of the WBD must include a mechanism for ensuring identified problems get fixed. This could come from within an agency or be provided as part of the deployment, but appears necessary if diagnostics are to do more than simply identify problems and actually proceed to deliver energy savings.

2 Purpose of This Task Report

In April 2000, the California Energy Commission (Commission) initiated a project to evaluate a DOE-developed technology, the Whole-Building Diagnostician (WBD), for automatically and continually diagnosing operational problems in buildings. The WBD is a pre-commercial, production-prototype software package that connects to digital control systems (e.g. energy management systems), utilizing data from the control system's sensors to analyze overall building and system performance. It currently consists of two diagnostic tools, or modules, with a user interface designed to readily identify problems and provide potential solutions to building operators. The Outdoor-Air/Economizer module (OAE), the subject of this demonstration, diagnoses whether each air handler in a building is supplying adequate outdoor air for the occupants it is designed to serve, by time of day and day of week. It also determines whether the economizer is providing free cooling with outside air when appropriate and not wasting energy by supplying excess outside air. In addition to the two diagnostic modules, the WBD also has a data collection module to automatically retrieve data from some building automation systems.

This report documents the results of **Task 2.4.15 – On-line Test for the Service Provider Demonstration for Project 2.4 – Demonstration of the Whole-Building Diagnostician.** The service provider demonstration was conducted at the Capitol Mall building in Sacramento. Some characteristics of the building are listed in the next section.

This project is intended to demonstrate the WBD's current automated diagnostic tools in three contexts:

- **Single-Building Operator Demonstration –** use of the WBD by dedicated operators for a single, Class A office building
- **Multi-Building Operator Demonstration –** use of the WBD by a set of supervisory operators for a set of commonly managed and operated buildings that share a control system infrastructure
- **Service Provider Demonstration –** use of the WBD by third-party analysts of a service company providing contracted retrofit and O&M services to buildings and facilities.

In each of these three contexts, Project 2.4 is designed to test and demonstrate automated diagnostics using the WBD in actual buildings with actual operators and energy service providers to:

- Prove their efficacy in automatically detecting energy efficiency and outdoor-air supply problems in buildings
- Test and demonstrate the ability of users to interpret and act upon the information provided by the tools to correct building operational problems
- Develop case studies of the impacts of using the tools in terms of the type and number of problems found, the energy savings and fresh air supply impacts of correcting the problems, and
- Provide early feedback from users, based on their experiences with actual automated diagnostic tools, to guide development and implementation of other tools in the future, including those in the program plan.

This report focuses on the on-line test results for the Service Provider demonstration and is a follow up to an earlier report that described the off-line test results for the same site. This demonstration, which is the third and final demonstration, is intended to test the ability of a third-party service provider to use and interpret the results from the WBD tool. The first demonstration was to test the WBD tool in a single-building with a single operator. The second demonstration was to test the WBD in a multi-building, multi-operator environment. The results from the first two demonstrations are reported in companion reports.

After the demonstration site was selected, the demonstrations began with an off-line test of the WBD's Outdoor-Air Economizer (OAE) diagnostic module. The off-line test was designed to determine the basic suitability of the demonstration site for testing the WBD. The three major criteria to determine the suitability were: accessibility of the control system sensors for data collection, whether the necessary sensors were present and reasonably accurate, and whether the control strategy for the air handler's outdoor-air economizer systems could be diagnosed by the OAE module. Off-line testing of the OAE module at Capitol Mall was successful because all three major criteria were satisfied.

The results of the on-line demonstration are presented in this report. In the section following this, the need for diagnostics in building systems is briefly discussed, followed by a section on basic information about what the WBD is, how it works, and a detailed description and capabilities of the OAE module. The Capitol Mall building is described next. Technical discussions including installation of the WBD, training of the Capitol Mall Service Provider staff, the WBD's operation, problems identified by the OAE, potential savings from correctly the problems found, and issues that surfaced that have implications for facilities that might wish to use the WBD are also presented.

3 Capitol Mall Building

The service provider demonstration took place at the Capitol Mall Building in Sacramento. The Capitol Mall building is an 18-story 385,000 square foot premier “Class A” office building with integral covered parking structure. The building, other than office space, houses a Café, rooftop terrace and balconies. The building was built in 1984 and is located at 300 Capitol Mall approximately six blocks west of the State Capitol. The building is an Environmental Protection Agency “Energy Star” qualified building. Buildings, which are “Energy Star” qualified, use about 40 percent less energy than average buildings, without compromising comfort or services.

Dave Maron, of BayPoint Controls a division of Marina Mechanical, the controls service provider, and Battelle selected the building at 300 Capital Mall for the demonstration. The site was selected because it was readily accessible and had a suitable climate. Off-line data were collected for a period between May 17, 2001 and May 24, 2001 and the on-line data between September 19, 2002 and March 27, 2003.

Building operations have been contracted to Able Engineering Services through Jones Lang La Salle, Americas Inc., the building’s on-site management, with 24/7 on site engineering services. In addition to the on-site engineering services, services are subcontracted to Marina Mechanical, which provides the building controls and heating, ventilation and air-conditioning (HVAC) services. Able Engineering Services provides engineering services nation wide and maintains over 170,000,000 square feet of commercial office, hotels, hospitals, data centers, and other large complexes Jones Lang LaSalle is a global provider of comprehensive real estate and investment management services which serve clients locally, regionally and internationally from offices in over 100 markets on five continents. Marina Mechanical is a mechanical contractor which provides HVAC and Indoor Air Quality (IAQ) services including consulting, design, construction, maintenance, 24 hour service, automated temperature controls, process piping and specialized ventilation systems. The engineering services team has maintained optimal equipment performance and has performed various lighting, mechanical, plumbing, and controls enhancements.

The buildings HVAC systems consist of two variable speed drive centrifugal chillers of 500 tons each and one natural gas hydronic boiler of 7,000,000 Btu/hr., both hydronic systems are constant volume. Six large variable-air-volume (VAV) air handlers with heating and cooling coils, differential dry-bulb controlled economizers and variable speed drives (see **Table 1**) serve the occupied space. The air-handlers provide heating and cooling to the occupied spaces through variable volume zone boxes without reheat coils. A direct digital control (DDC) system from American Auto-Matrix controls the HVAC systems, which also provides a mechanism for trend logs.

Table 1 – Capitol Mall Air Handlers in the Demonstration

Air-Handler	Rated Flow (ft^3/min)
AHU-1	100,000
AHU-2	100,000
AHU-3	40,000
AHU-4	40,000
AHU-5	50,000
AHU-6	50,000

Note: Air handler rated flow is the design rating

The primary contacts at Capitol Mall were Dave Maron and Jim Hussey, of Marina Mechanical, the site controls contractor and Ken Van Duyn, of Able Engineering Services, the building's onsite Chief Engineer. Dave Maron was the primary administrator of the WBD at Capitol Mall (The Administrator has the highest-level permissions to change the configuration of the WBD to reflect changes to controls, add diagnosticians, rename buildings and components, reprocess data, etc.).

Capitol Mall is the third demonstration of the WBD at a private-sector building; the first was done at a large hotel in San Francisco and the second was done at a large office building in San Diego.

4 The Need for Diagnostics in Building Systems

Automated commissioning and diagnostic technologies are designed to ensure the ongoing performance of buildings at the highest possible levels of efficiency. Evidence of extensive performance problems in buildings shows that an efficient building stock will not result from solely designing efficient buildings and installing efficient equipment in them (Lunneberg 1999; also check the commissioning resources at http://www.peci.org).

These performance problems are not inherent with efficiency technologies themselves, but instead result from errors in installation and operation of complex building heating/cooling systems and their controls. It is also significant that these systems are becoming increasingly more sophisticated to obtain ever-higher levels of energy efficiency, adding to the complexity and subtlety of problems that reduce the net efficiency acquired. Such problems are even more common in existing buildings because they arise over time from operational changes and lack of maintenance (Claridge et al. 2000; also check the commissioning resources at http://www.peci.org). They often result in problems with comfort control and indoor-air quality that affect occupant health and productivity (Daisey and Angell 1998).

Assuring efficient performance by commissioning of new buildings followed by regularly scheduled preventative maintenance is clearly insufficient to address this issue. Manually commissioning[1] of buildings is valuable in terms of both finding problems and developing the techniques for doing so, but it is expensive. With only 1 to 2% of total construction costs devoted to commissioning (see the commissioning resources at http://www.peci.org) and the few experts available to provide such services in high demand, commissioning is not done adequately for most commercial buildings. Commissioning is difficult to sell in a low-bid construction environment, where variations in the effort allocated to commissioning can be the difference between winning and losing bids and where building owners (rightfully) feel they should not have to pay extra to get buildings to work properly. Further, commissioning is often short-changed because it largely occurs at the end of the construction process, when time-to-occupancy is critical and cost overruns drive last minute budget cuts in remaining items.

Effective, on-going maintenance of building systems as usually performed is notably ineffective, being almost exclusively complaint-driven and "quick fix" oriented. This is especially true for problems affecting air quality and efficiency because they are "silent killers" that go unnoticed until complete system failure occurs.

By embedding the expertise required to detect and diagnose operation problems in software tools that leverage existing sensors and control systems, detection and diagnosis can be conducted automatically and comprehensively without the ongoing cost of expensive human expertise. Further, this oversight remains as a legacy in buildings after they are constructed, protecting the

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[1] Commissioning is the process of systematically putting a building "through its paces," checking that it performs as expected in terms of sensor and actuator connectivity and calibration, system modes, control sequences, and equipment capacities and conversion efficiencies. The term derives from the traditional acceptance process for naval ships, which must undergo a shakedown cruise to prove their speed, range, stability, maneuverability, communications, etc., to meet design specifications before they are accepted into service.

building systems against slow mechanical degradation, as well as faults inadvertently introduced by operators seeking to resolve complaints without finding root causes. The principal technical challenges are the construction of diagnostic techniques that 1) can be automated, 2) comprehensively diagnose the range and diversity of building systems and equipment, 3) make use of a minimal set of additional sensors beyond those used for control, and 4) are applicable for building commissioning, as well as ongoing diagnostics.

Currently, most building owners are not aware of the power of automated commissioning and diagnostic technology to provide them more cost effective, comfortable, and productive buildings. The technology is in its infancy and not yet well known in practice. Finally, energy service companies who may eventually offer commissioning and diagnostic services are slow to expand their business practices beyond their current focus on lighting and cooling equipment retrofits. Despite this current state, automated diagnostic technology offers a promising future with improved facility operation, better indoor environments, and enhanced and higher-quality offerings by service companies.

5 Background on the WBD

Developed by the Pacific Northwest National Laboratory (PNNL)[2] under funding from the Office of Energy Efficiency and Renewable Energy of the U.S. Department of Energy, with Honeywell, Inc. and the University of Colorado as subcontractors, the Whole-Building Diagnostician (WBD) is a production-prototype software package with two modules providing automated diagnostics for buildings based on data collected by direct-digital control (DDC) systems. These tools are deployed in the WBD's user interface and data and process management infrastructure.

The WBD's Outdoor-Air Economizer module diagnoses whether each air handler in a building is supplying adequate outdoor air for the occupants it is designed to serve, by time of day and day of week. It also determines whether the economizer is providing free cooling with outdoor air when appropriate, and is not wasting energy by supplying excess outdoor air. Few, if any, sensors other than those used to control most economizers are required, making the OAE practical in near-term markets because of its low cost. Early experience with the OAE in new and existing buildings in Washington and California has confirmed the broadly held suspicion that problems with outdoor-air ventilation control and economizing are endemic. The OAE has discovered problems in all but 1 of the roughly 35 air handlers examined to date, in existing and newly commissioned buildings.

The WBD also contains a Whole-Building Efficiency module that monitors whole-building and major subsystem (end-use) performance. It does this by tracking actual energy consumption and comparing it to estimated expected consumption as a function of time of day, day of week, and weather conditions. Using these data, it automatically constructs a model based on actual past system performance for a baseline period, and then alerts the user when performance is no longer as good as or, in the case of retrofits or operations and maintenance (O&M) programs, is better than past performance. The tool bootstraps itself to provide feedback during the initial training period after a period of about 4 to 6 weeks. Electricity or gas consumption sensors typically must be connected to the building's direct digital control (DDC) system to obtain the consumption data. This, however, is not an absolute requirement.

Both modules provide information to users in simple, graphical displays that indicate the presence or absence of problems at a glance. They also provide cost estimates of detected energy waste to provide feedback to users on the relative importance of the problems detected. These tools are available for commercialization through special use licenses from Battelle. The WBD's infrastructure is an open-protocol, public-domain framework designed to support the ready incorporation of new diagnostic tools from other developers in the future.

5.1 The WBD Infrastructure

The WBD currently consists of four primary modules: the two diagnostic modules, the user interface, and a database that stores measured data, as well as diagnostic results. These are connected by an infrastructure that provides data transfer, data management, and process control, as shown in Figure 1. Boxes represent major components; lines represent flows of data. Data is

[2] Operated for the U.S. Department of Energy by Battelle Memorial Institute under Contract DE-AC06-76RL01830.

automatically obtained at a user-specified sub-hourly frequency and averaged to create hourly values. As new hourly values become available in the database, the diagnostic modules automatically process them and produce diagnostic results that are also placed in the database. The user can then open the WBD user interface at any time to see the latest diagnostic results, and can also browse historical results.

Raw data (e.g., sensor measurements) may be obtained from a variety of data sources: a data logger or building management system, another database, or some other analytic software tool. The system also requires one-time entry of setup data that customizes the WBD modules to each specific building and heating/cooling/ventilation system. The system is written in the C++ language and uses an SQL database. The term DDE in Figure 1 refers to Microsoft's Dynamic Data Exchange protocol.

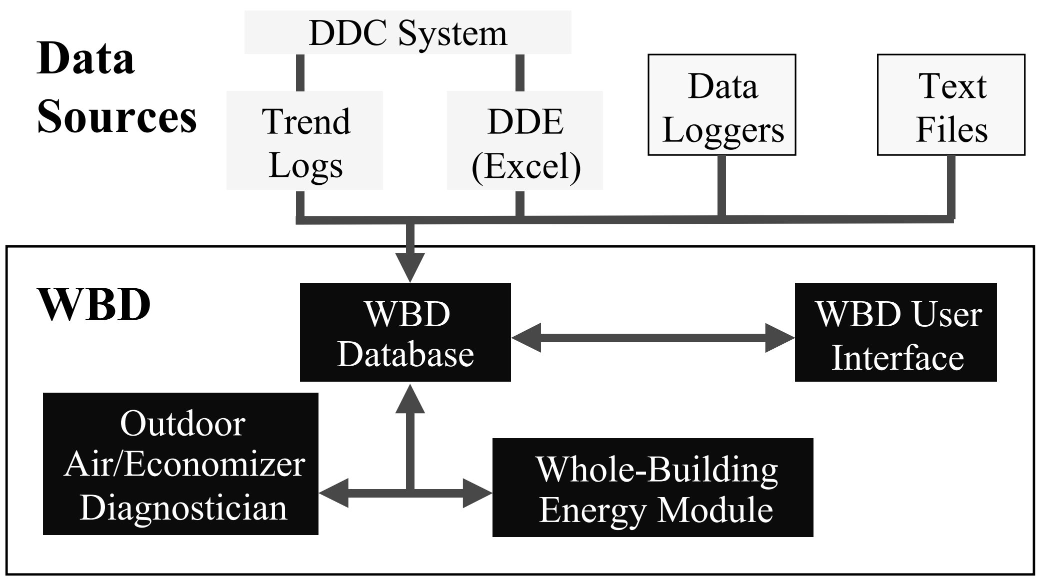

Figure 1 – Schematic Diagram of the WBD Software

6 The Outside-Air Economizer (OAE) Diagnostic Module

This section provides a brief overview of the Outside-Air Economizer (OAE) module. Additional information about the WBD and the OAE can be found in Brambley et al. (1998) and Katipamula et al. (1999). The OAE continuously monitors the performance of air handlers and can detect basic operation problems or faults with outside-air control and economizer operation. The current version detects about 25 different basic operation problems and over 100 variations of them [for details refer to Brambley et al. (1998) or Katipamula et al. (1999)]. It uses color-coding to alert the building operator when problems occur and then provides assistance in identifying the causes of problems and advice for correcting them. It, however, does not detect problems with the waterside or the refrigerant side of the air handler; it only detects problems on the airside, i.e., economizer operation and ventilation. If the air handler does not have an economizer, the OAE module can still detect problems with the outdoor-air ventilation.

6.1 Types of Economizer Controls Supported

The OAE module can diagnose abnormal operations or problems with several different types of economizer controls including: differential dry-bulb temperature-based, differential enthalpy-based, high-limit dry-bulb temperature-based and high-limit enthalpy-based.

With differential control strategies, the outside-air condition is compared with the return-air condition. As long as the outside-air condition is more favorable (for example, with dry-bulb temperature control, the outside-air dry-bulb temperature is less than the return-air temperature), outside air is used to meet all or part of the cooling demand. If the outside air alone cannot satisfy the cooling demand, mechanical cooling is used to provide the remainder of the cooling load.

With high-limit control strategies, the outside-air condition is compared to a single or fixed set point (usually referred to as a high limit). If the outside-air condition is below the set point, outside air is used to meet all or part of the cooling demand. Mechanical cooling provides any remaining cooling load.

In addition to these economizer control strategies, the OAE supports fault detection with both integrated and nonintegrated economizers. An integrated economizer, as its name implies, is fully integrated with the mechanical cooling system such that it can either provide all of the building's cooling requirements if outdoor conditions allow, or it can supplement the mechanical cooling when outdoor conditions are not sufficiently favorable to handle the entire cooling load. An economizer often has the ability to throttle outdoor-air intake rates between minimum and maximum levels to prevent the delivered air from being cooler than the supply-air set point.

Conversely a nonintegrated economizer does not operate when the mechanical cooling system is operating. If outdoor conditions are not sufficiently favorable to allow 100% economizing, no economizing is used. A two-stage thermostat often controls a nonintegrated economizer. The first stage opens the economizer; the second stage locks out the economizer and turns on the mechanical cooling.

6.2 Types of Air-Handling Systems Supported

The OAE tool supports the following types of single-duct air handlers:

- Constant-air-volume systems

- Variable-air-volume (VAV) systems with no volume compensation (i.e., outside-air intake is a constant fraction of the supply-air flow rate rather than changing it to maintain a constant outside-air volume).

Air handlers that the OAE tool does not support include:

- VAV systems that maintain constant outside-air volume flow through volumetric flow measurements (commonly using air-monitoring stations consisting of pitot-tube arrays)

- VAV systems that attempt to approximately provide constant outside-air volumetric flow by increasing the outside-air fraction (e.g., by opening the outside-air damper system) as the fan speed decreases

- Systems that utilize CO_2-based outside-air control strategies

- Dual-duct air-handling systems.

6.3 Metered Data Requirements for the OAE Module

The OAE requires seven periodically measured/collected (currently at sub-hourly increments) variables, as shown in Figure 2 (bold labels in the figure identify required data). In addition to the seven variables, the damper-position signal is also required for air handlers with damper-position-signal control, i.e., if the damper-position signal is controlled directly to maintain the ventilation or to control the supply- or mixed-air temperatures when the air handler is economizing. For economizers with enthalpy-based control, outside- and return-air relative humidity's (only for differential enthalpy control) or dew point temperatures are required. If the supply- or mixed-air temperature set point is reset, the reset value at each hour is also needed.

6.4 Setup Data Requirements

The OAE module requires several one-time (setup or configuration) data inputs to characterize the existing systems and how they are controlled. In addition to the setup data, the OAE also requires at least seven metered data points (same as variables called out in Figure 2). The engineering units for all inputs (both setup and measured) are assumed to be in Inch-Pound units unless otherwise specified.

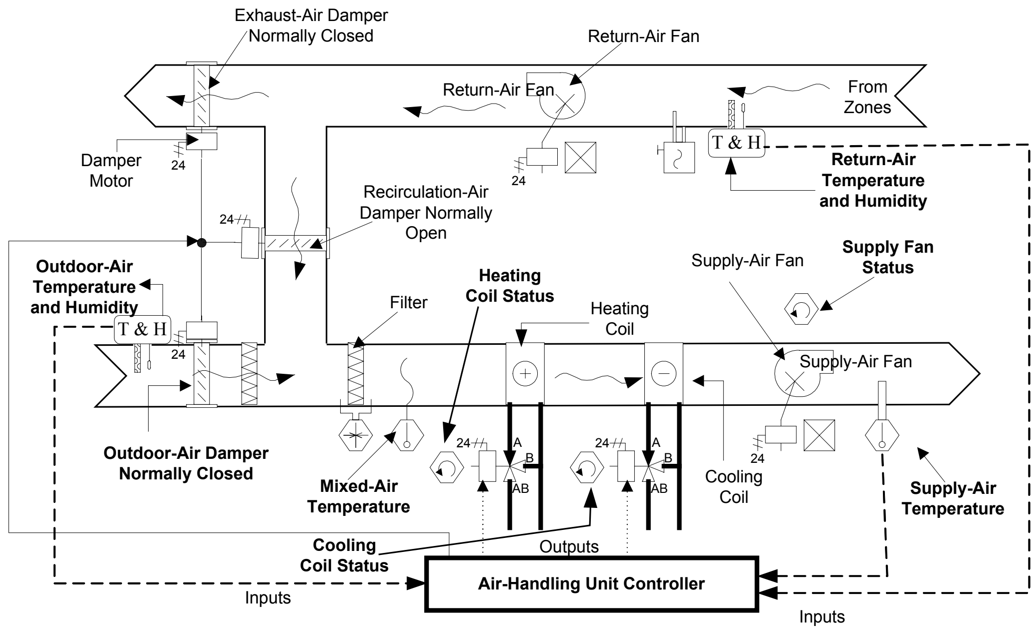

Figure 2 – Schematic Diagram of an Air Handler Showing the Sensor Locations

The OAE is capable of detecting and diagnosing faults with most commonly found air handlers using almost all outside-air and economizer control strategies. However, the user must describe the control strategies used to the OAE with the setup information. In addition, the OAE is designed to be flexible in accepting status inputs. For example, the WBD can accept any one of four different types of signals to indicate whether the supply fan is ON. Once the OAE module is configured, the detection and diagnosis is fully automated.

The setup data are required for all air-handler systems with economizers. These data describe:

1. The basic air-handling system
2. The minimum, maximum, and required (building fully-occupied) outdoor-air fractions
3. The occupancy schedule, defining when the required outdoor air must be supplied
4. Data needed to estimate energy and cost impacts of problems.

There are 17 items of user-supplied setup data that must be supplied for every air-handler system. In addition, there are a number of additional setup data inputs, along with the types of air handler and economizer controls to which they are applied. As few as 3 to as many as 15 additional inputs may be required to describe any given system type. For a typical system with an outdoor-air-fraction-based differential temperature economizer with low-limit control, nine of these setup items are required. Almost all of these inputs are provided with defaults that enable the OAE module to be initialized without the user providing them; however, it will not provide correct diagnoses unless the setup values are correct. Potential errors in the setup data are sometimes identified by the OAE as candidate causes of problems it detects with the air-handler operation. Generally, these then need to be reconciled by the building operator and setup data changed to correct any differences between the actual and default values.

6.5 Basic Operating Sequence of Air Handlers

The OAE module uses a logic tree to determine the operational "state" of outdoor-air ventilation and economizer systems at each point in time for which measured data are available. The logic tree is based on the basic air-handler operating sequence, as described below.

An air handler typically has two main controllers: 1) to control the outdoor-air intake and 2) to control the supply-air temperature (in some cases mixed-air temperature is controlled rather than supply-air temperature). The basic operation of the air handler is to draw in outdoor air and mix it with return air from the zones and, if necessary, condition it before supplying the air back to the zones, as shown in Figure 2.

An air handler typically has four primary modes of operation during a building's occupied periods, for maintaining ventilation (fresh-air intake) and comfort (the supply-air temperature at the set point), as shown in Figure 3. The operating sequence determines the mode of operation and is based on the ventilation requirements, the internal and external thermal loads, and indoor and outdoor conditions.

When indoor conditions call for heating, the heating-coil valve is modulated (i.e., controlled) to maintain the supply-air temperature at its set point (heating mode in Figure 3). When the air handler is in the heating mode, the cooling-coil valve is fully closed, and the outdoor-air damper is positioned to provide the minimum outdoor air required to satisfy the ventilation requirements. As heat gains increase in the zone and the need for cooling increases, the air handler transitions from heating to cooling. Before mechanical cooling is provided, the outdoor-air dampers are opened fully to use the favorable outdoor conditions to provide 100% cooling (economizer mode in Figure 3). In this mode, the heating- and the cooling-coil valves are fully closed and the outdoor-air dampers are modulated to meet all the cooling requirements.

As the heat gains in the zone continue to increase, the outdoor air alone cannot provide all the cooling necessary, and the air handler changes modes by initiating mechanical cooling (cooling and economizing mode in Figure 3) to supplement the economizer. In this mode, the outdoor damper is fully open, the heating-coil valve is fully closed, and the cooling-coil valve is modulated to maintain the supply-air temperature. As the outdoor conditions become unfavorable (i.e., too hot and humid) for economizing, the air handler changes mode again. This time the outdoor-air dampers are modulated to the minimum position to provide the minimum outdoor air required to satisfy the outdoor-air ventilation needs, the heating-coil valve continues to be fully closed, and the cooling-coil valve is modulated to maintain the supply-air temperature at its set point.

If an air handler does not have an economizer, there are two basic modes of operation (heating and mechanical cooling). If the economizer is not integrated with mechanical cooling (i.e., it cannot economize and provide mechanical cooling simultaneously), there are three basic modes of operation (heating, economizing, and mechanical cooling).

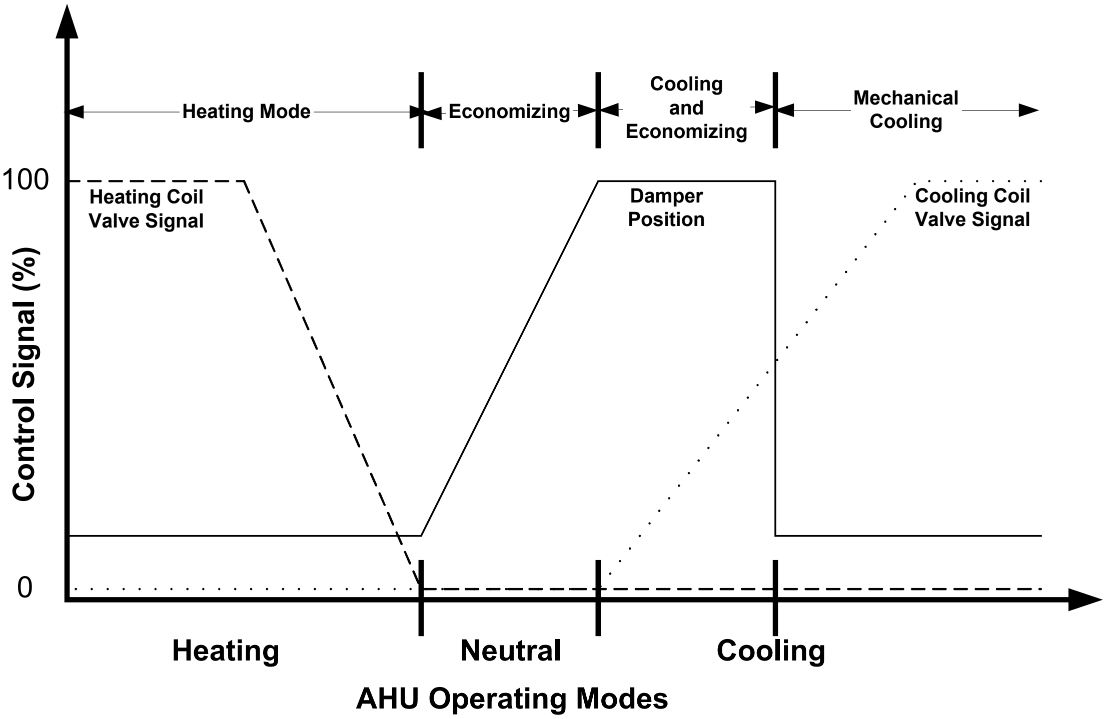

Figure 3 – Basic Operating Sequence of an Air-Handling Unit

6.6 Diagnostic Approach

The OAE uses rules derived from engineering models and understanding of proper and improper air-handler performance to diagnose operating conditions. The rules are implemented in a decision tree structure in the software. The OAE diagnostician uses periodically measured conditions (temperature or enthalpy) of the various airflow streams, measured outdoor conditions, and status information (e.g., fan on/off status) to navigate the decision tree and reach conclusions regarding the operating state of the air handler. At each point in the tree, a rule is evaluated based on the data, and the result determines which branch the diagnosis follows. A conclusion is reached regarding the operational state of the air handler when the end of a branch is reached. Tolerances are assigned to each data point, and uncertainty is propagated through all calculations.

Many of the states correspond to normal operation and are dubbed "OK states." For example, one OK state is described as "ventilation and economizer OK; the economizer is correctly operating (fully open), and ventilation is more than adequate." For this case, the system is apparently operating correctly with the outdoor-air damper fully open to benefit to the maximum extent possible from cool outdoor-air used for free cooling. Ventilation rates for the occupants are also being met by the current outdoor-air ventilation rate. Other states correspond to something operationally wrong with the system and are referred to as "problem states." An example problem state might be described as "economizer should not be off; cooling energy is being wasted because the economizer is not operating; it should be fully open to utilize cool outside air; ventilation is adequate." As with the previous state, conditions are such that the outside-air damper should be fully open to benefit from free cooling; however, in this case the economizer is incorrectly off, yet the outdoor-air ventilation is still adequate to meet occupant needs. Thus, the building is experiencing an energy penalty from not using the economizer. Other states (both OK and problem) may be tagged as incomplete diagnoses, if critical data are missing or results are too uncertain to reasonably reach a conclusion.

Each problem state known by the OAE module has an associated list of possible failures that could have caused the state; these are identified as possible causes. In the example above, a stuck outdoor-air damper, an economizer controller failure, or perhaps a miss-configured setup could cause the economizer to be off. Thus, at each metered time period, a list of possible causes is generated.

An overview of the logic tree used to identify operational states and to build the lists of possible failures is illustrated in Figure 4. The boxes represent major sub-processes necessary to determine the operating state of the air handler; diamonds represent tests (decisions), and ovals represent end states and contain brief descriptions of OK and problem states. Only selected end states are shown in this overview, and the details of processes and decisions are excluded because of space constraints.

6.7 Basic OAE Functionality

The OAE user interface uses color-coding to alert the building operator when problems occur. It then provides assistance in identifying the causes of the problems detected and in correcting them. Figure 5, for example, shows a representative OAE diagnostician window. On the left pane of the window is a directory tree showing the various systems implemented in this particular WBD system. The tree can be used to navigate among the diagnostic results for various systems. In this case, results for air handler 12 (AHU-12) are highlighted in the tree. In the right pane is a color map, which shows the OAE diagnostic results for this air handler. Each cell in the map represents an hour. The color of the cell indicates the type of state. White cells identify OK states, for which no problems were detected. Other colors represent problem states. "Clicking" the computer mouse on any shaded cell brings up the specific detailed diagnostic results for that hour.

Figure 6 and Figure 7 show pop-up windows providing a short description of a problem, a more detailed explanation of the problem, energy impacts of the problem, potential causes, and suggested actions to correct each cause. The second window (Figure 7) labeled “Details” is revealed by "clicking" on the "Details" button in the first window (Figure 6). In this case, the problem investigated is a sensor problem. The current version of this OAE diagnostician cannot, by itself, isolate the specific sensor that has failed, but instead it suggests manual inspection and testing of the sensors and their wiring to identify the specific problem. Yet another example of OAE is shown in Figure 8, where a high-energy consumption problem is evident.

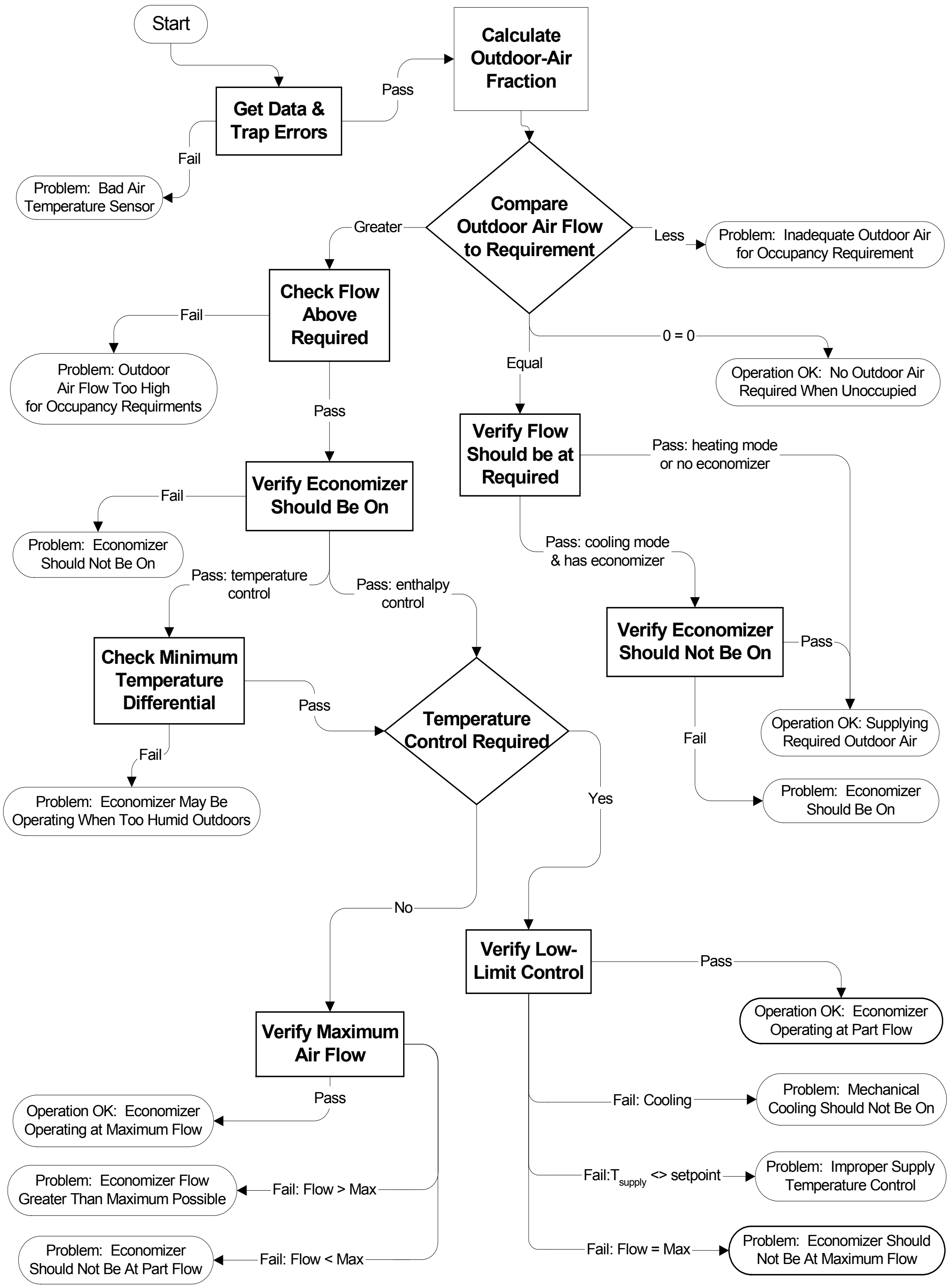

Figure 4 – Overview of the OAE Diagnostic Logic Tree Showing Key Decision Processes in Boxes and Operating States in Ovals

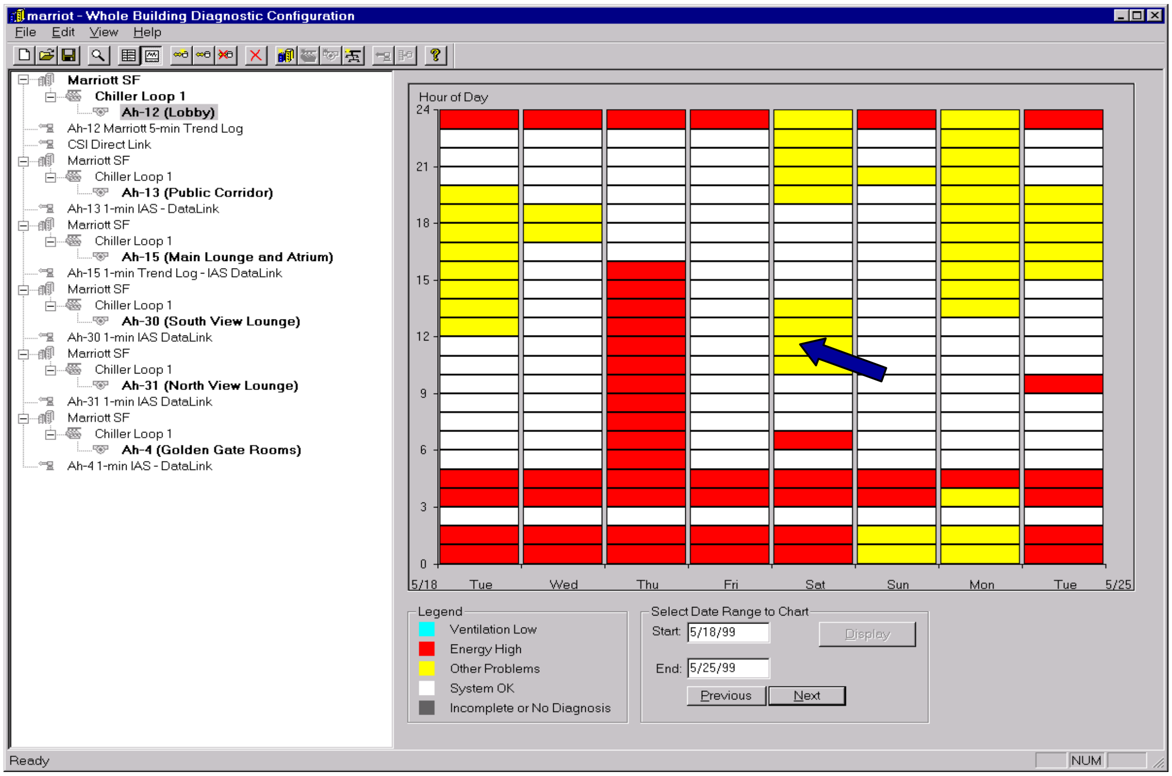

Figure 5 – Diagnostic Results Showing Proper and Faulty Operation for an Air Handler with a Faulty Outdoor-Air Temperature Sensor. The arrow identifies the cell for which more detailed results are given in Figure 6 and Figure 7

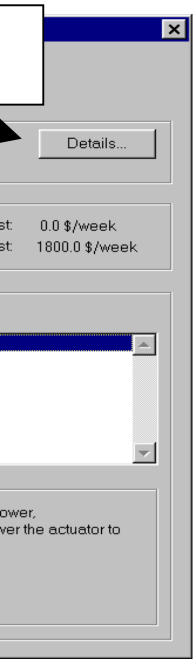

Figure 6 – Window Showing a Description of the Diagnosis, the Impacts of the Problem Found, Potential Causes of the Problem, and Suggested Corrective Actions.

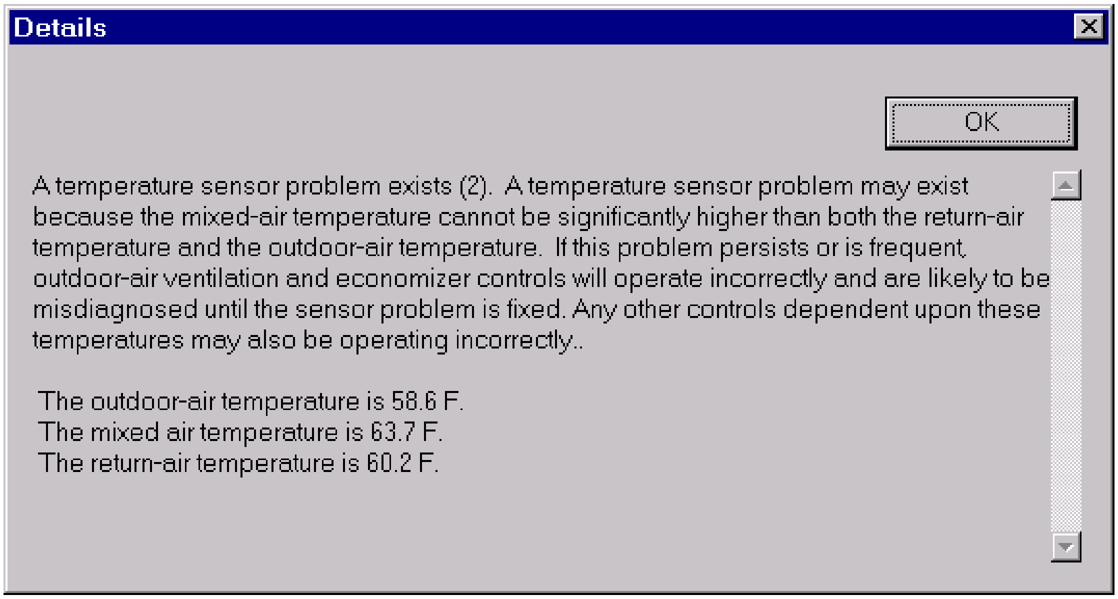

Figure 7 – "Details" Window Showing a Detailed Description of the Temperature Sensor Problem Identified in Figure 5

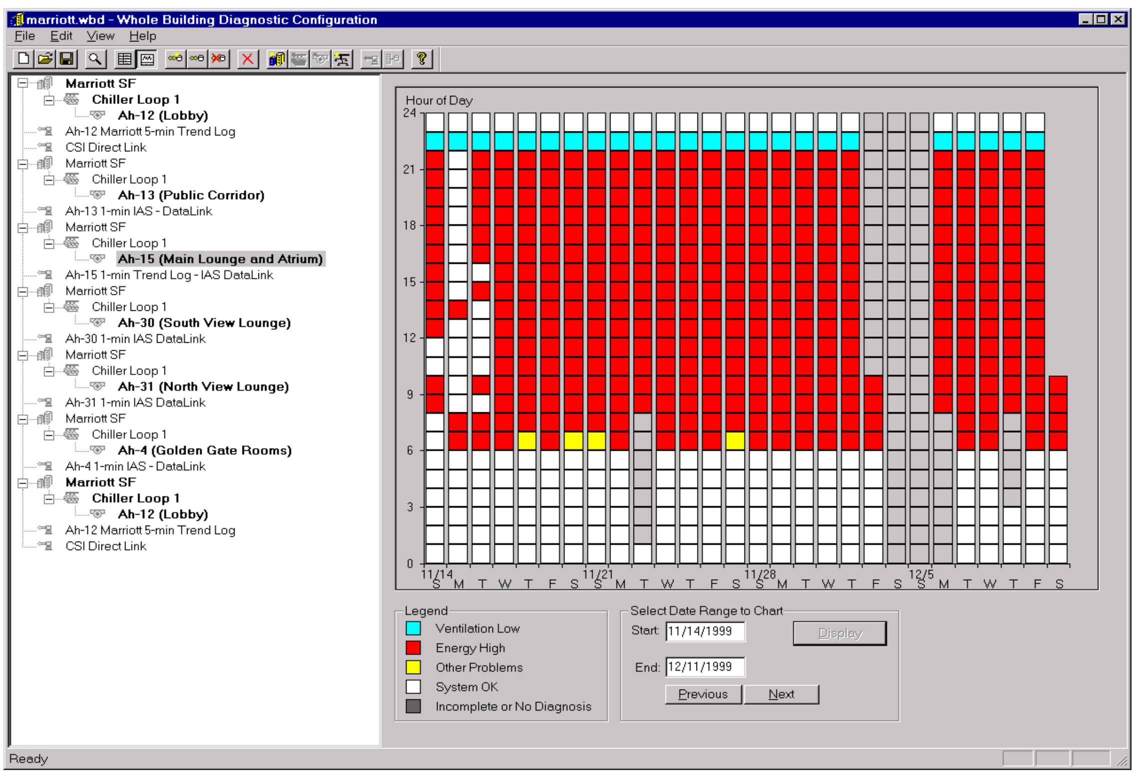

Figure 8 – An Example OAE display is shown for Air Handler 15 for November 14 through December 11. A high-energy consumption problem is clearly evident throughout this time period.

6.8 Requirements for Using the WBD and OAE

The WBD and its diagnostic modules were developed for a personal computer running any Microsoft Windows operating system (98/ME/NT/2000/XP)[3]. The WBD can be run in a fully automated/unattended mode or can be used to batch process the data. To run the WBD in a fully automated (unattended) mode, the data collection from the air handlers to the WBD database must be fully automated. A companion data collection module can be used to collect the data from air handlers that are controlled by central building automation systems. To use this data collection module, the site needs a networked computer operating under Windows 98/NT/2000 (preferably NT or 2000 to avoid problems with the computer's clock) and a building automation system (BAS) that support Microsoft DDE protocols. There are other methods available for data collection; however, several of the current methods may require increased levels of human intervention (see Figure 1).

Although the underlying methodology used by the OAE is independent of the time interval at which data are collected, the user interface can only display results at hourly intervals. Therefore, all data should be at least at an hourly resolution. The data collection module can process data that is more frequent (5-minute intervals, for example) and average it to hourly values. Instantaneous values obtained on 5-minute intervals or less, and averaged to form hourly data, are recommended. It is preferable to have all measured data either instantaneous or averaged. Mixing instantaneous and averaged data may introduce false alarms and therefore is not recommended.

[3] Although the initial version of the WBD and its components were developed and tested under the Windows 95 operating system, this operating systems in not currently supported.

7 Summary of Off-line Results for Capitol Mall

The data for the off-line tests for the six air handlers were collected using the trending feature of the existing building automation system at Capitol Mall. Data specified was collected between May 17, 2001, and May 24, 2001, on five-minute intervals. There were no major gaps in the data. A typical section of the data after it was assembled into a single file is shown in Table 2.

Results from the off-line tests indicated significant potential problems in 2 of the 6 air handlers examined with the OAE. Two of the six air handlers at 300 Capital Mall (AHU-1 and AHU-5) had significant indications of temperature sensor calibration problems, while the other four air handlers had some indication of excessive energy use in the morning hours but mostly correct operation at other times of the day. It was recommended that all air-temperature sensors in these air handlers be examined, recalibrated, and repositioned as necessary to correct the observed problems.

Table 2 – Typical Raw 5-Minute Data, 300 Capital Mall, in .*dif* format

Date	Time	SAT	MAT	RAT	OAT	Discharge Reset Setpoint	Damper Position (% open)	Heating valve position (% open)	Cooling valve position (% open)	Supply VFD Status
5/17/01	14:46		76.84	78.21	96.02	70.4	10	100	0	0
5/17/01	14:51	63.19	76.64	78.24	96.69	70.28	10	100	0	0
5/17/01	14:56	63.38	76.78	78.22	97.53	69.98	10	100	0	0.9125
5/17/01	15:01	63.41	76.85	78.29	98.11	70.4	10	100	0	0.9175
5/17/01	15:06	63.61	76.97	78.33	97.33	70.4	10	100	0	0.915
5/17/01	15:11	63.42	77.12	78.37	99.66	70.7	10	100	0	0.9275
5/17/01	15:16	63.43	76.98	78.36	100.1	70.28	10	100	0	0.9225
5/17/01	15:21	63.68	77.1	78.4	101.1	69.86	10	100	0	0.915
5/17/01	15:26	63.54	77.46	78.47	101.5	70.7	10	100	0	0.9125

Heading terminology:

MAT = mixed air temperature
OAT = outdoor air temperature
RAT = return air temperature
SAT = supply air temperature

7.1 Configuring the Diagnostician

The next step in conducting the off-line analysis was to specify each air handler's configuration for the WBD's OAE diagnostic module. There are two aspects of the air handler's operation that must be specified for the OAE: the control strategy for the outdoor-air and economizer and the schedule (times of day and days of week) for which the minimum outdoor air must be supplied for the occupants (i.e., the occupancy schedule).

The screenshot of the configuration screen of the WBD's user interface for AHU-1 at 300 Capital Mall is shown in Figure 9. The left side is the hierarchical "configuration tree," specified by the Administrator for a given WBD installation. In this case it is the 300 Capital Mall building and a data collection network at the highest level. Beneath the building is a heating/cooling plant, and the plant serving the air handlers. In the off-line test, six air handlers

(AHU-1 through AHU-6) are configured. When the user selects AHU-6 and the Configuration button on the toolbar is pushed, AHU-6's configuration is displayed, as shown in Figure 9.

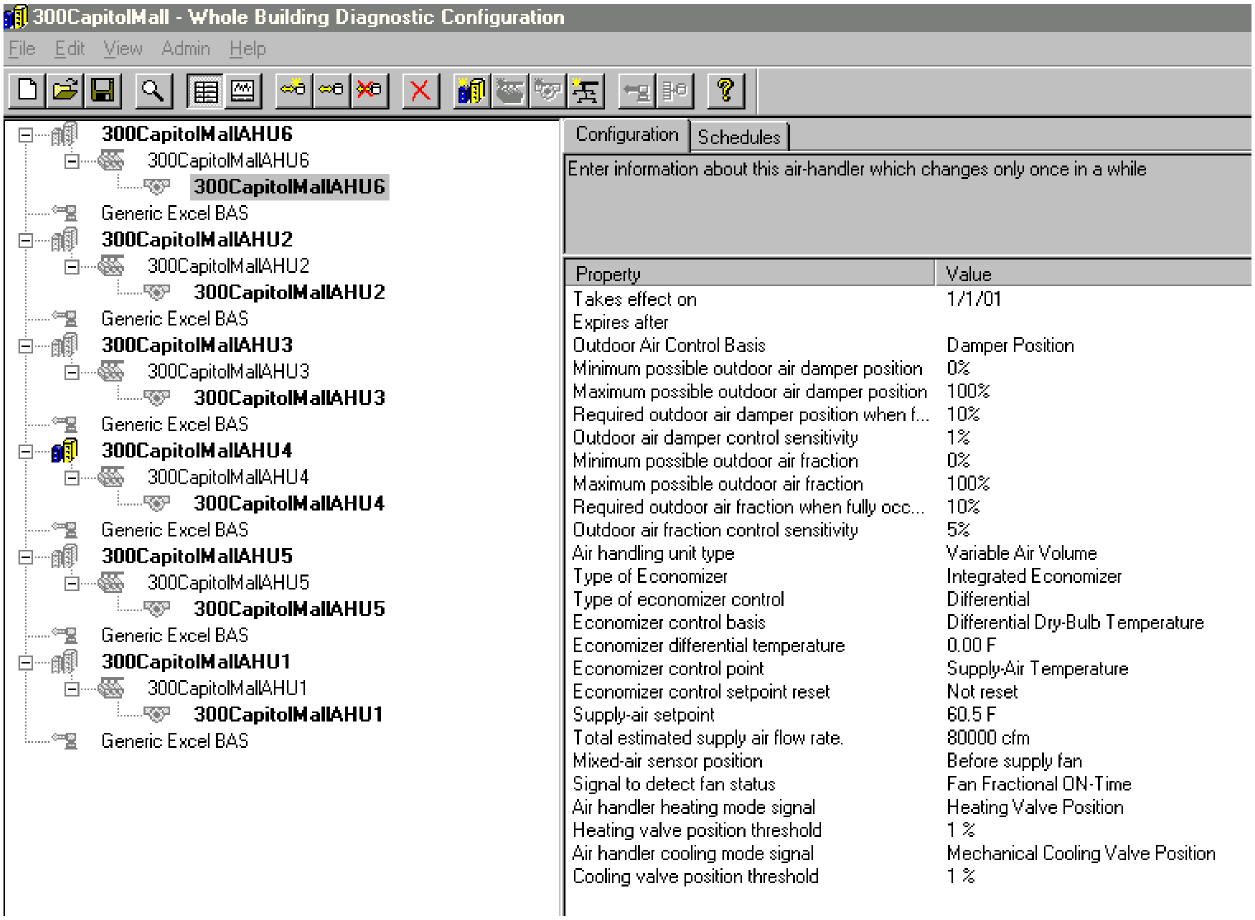

Figure 9 – WBD's Air Handler Configuration Screen (300 Capital Mall)

7.2 Air Handler Configuration Parameters

The air handlers at 300 Capital Mall are variable-air-volume type with nominal airflows shown in Table 3. Each has an integrated, differential economizer based on supply-air temperature set point. The set point for economizer operation appears to be reset, as average hourly supply temperatures range from 54 to 62°F, and are sometimes as high as 68°F. The economizer control set point is not reset.

Table 3 – 300 Capital Mall AHU Capacities

Air Handler	AHU-1	AHU-2	AHU-3	AHU-4	AHU-5	AHU-6
Air Flow (cfm)	100,000	100,000	40,000	40,000	50,000	50,000

For AHU-1, the outdoor-air damper system is controlled based on a specification of damper position (% open), with a minimum position during occupied hours of 10%, a maximum position of 100% during economizer operation, and a fully closed position that was not observed in the data provided but is presumed to be 0%. The damper position was assumed accurate to within +/-5% of its fully open position. These damper positions were assumed in configuration of the OAE module to correspond to outdoor-air fractions of 100%, 10%, and 0%, respectively. The 10% value was observed in most of the data analyzed; however, for each air handler, the first few hours of each day were consistently observed to have damper positions of up to 100%.

The remaining parameters specify the types of signals and thresholds used to determine whether the supply fan and heating and cooling modes for the air handler are on at a given time.

7.3 Off-line Test Results

The OAE diagnostic results for the period of the off-line analysis are displayed by the WBD's user interface, as shown in Figure 10. This view is displayed when the user selects AHU-1 on the configuration tree on the left side of the screen and pushes the *View diagnostic results* button on the toolbar. Each rectangle of the "color map" displays the diagnostic results for an hour, and each column of rectangles represents the results for one day. Each rectangle is color coded to indicate the general category of problem identified that hour, if any.

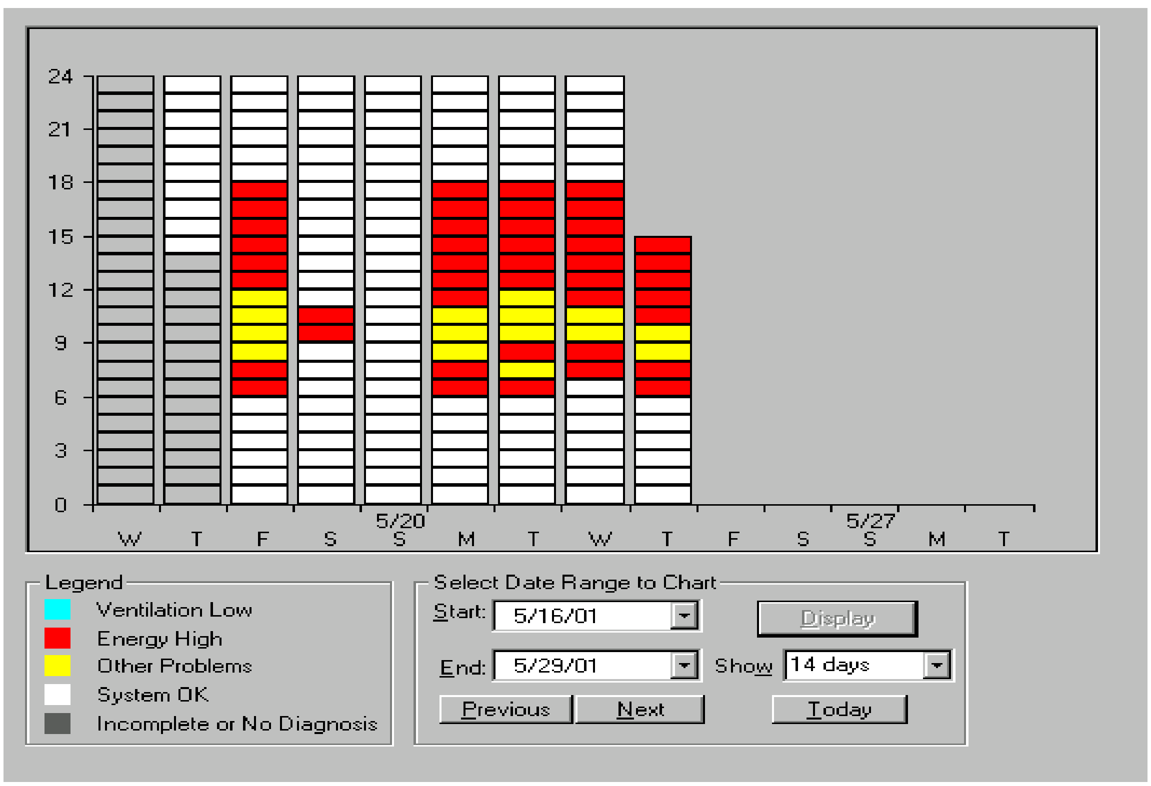

Figure 10 – WBD's Diagnostic Results View for AHU-1 at 300 Capital Mall.

As indicated in the legend in the lower part of the display, white cells indicate no problem was detected. White cells were generally found for this air handler when the AHU was not operating. However, when the AHU was operating, the problems were indicated by red and yellow cells.

Red cells indicate that energy is somehow being wasted in a number of possible ways. Clicking on one of the red cells in this case brings up another window, shown in Figure 11, that describes possible causes of the current condition. In this case, the problem identified was that the economizer should be off, but it was operating. Possible causes are also listed; in this case, a temperature sensor problem was identified.

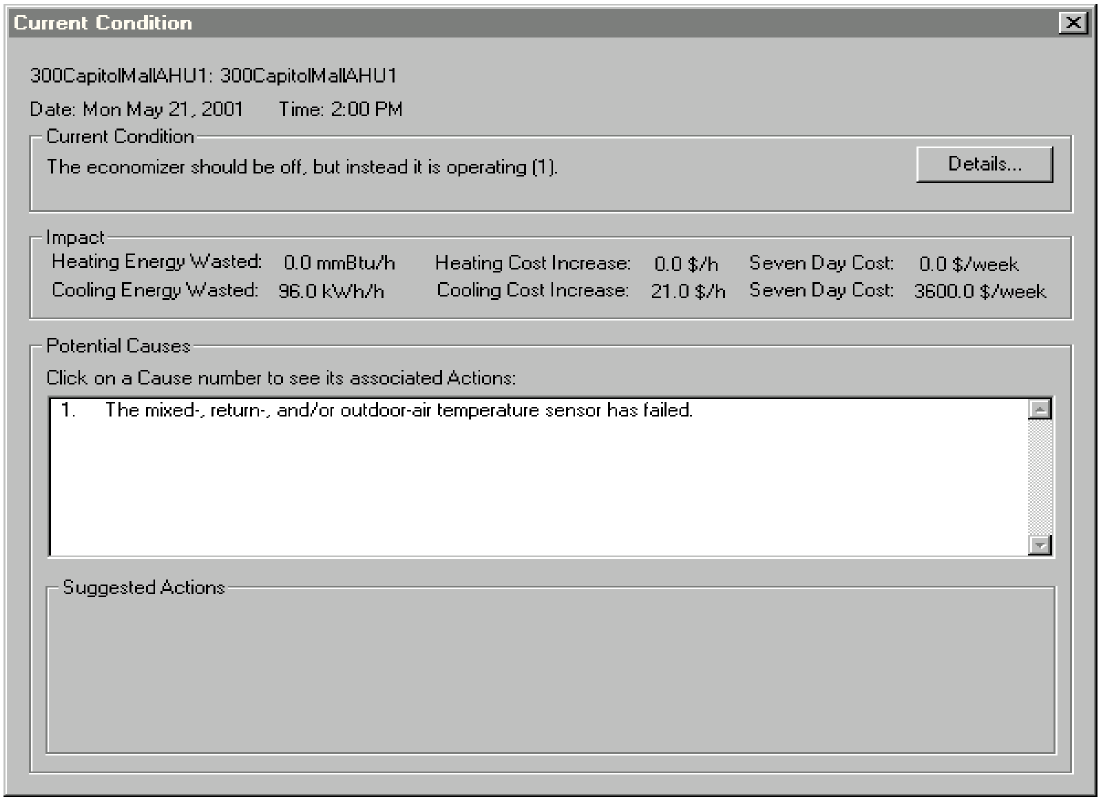

Figure 11 – Current Condition Dialogue for a Typical Red Square for AHU-1

Yellow cells indicate that there is a temperature sensor problem. This means that one of the temperatures has an unexpected value, and is likely out of calibration or broken. When these problems occur, the sensors should be examined and fixed or recalibrated, and the diagnostician re-run to detect whether other problems are present.

Clicking on the *Details* button on the Current Conditions Dialog provides additional information on the nature of the problem, as shown in Figure 12. This provides a more detailed description of the problem, and some key data to help interpret it. In this case, the mixed-air temperature is not in the range it is expected to be, which is between the outside-air and return-air temperatures.

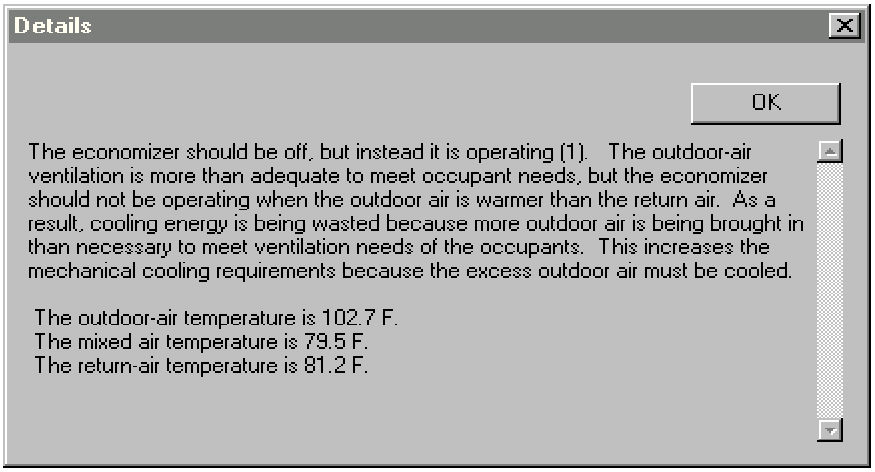

Figure 12 – Details on the Current Condition for a Red Square in AHU-1

7.4 Analysis of Trend Data

The user of the WBD is encouraged to visually inspect the pertinent equipment and to utilize the control system's capabilities to investigate problems further when the OAE detects problems but their exact causes are not isolated by it. In this off-line analysis, we examined the raw data provided, which in fact is identical with trend log data obtained from the control system.

7.5 Conclusions from Off-line Test

The problems found in the operation of the six air handlers at 300 Capital Mall were typically temperature sensor calibration or positioning problems, or excessive energy consumption problems, some of which could be traced back to temperature sensor problems. Two of the six air-handler diagnostics (AHU-1 and AHU-5) had significant indications of temperature sensor calibration problems (shown by the presence of yellow in the diagnostic screen), while the other four air handlers had some red ("excessive energy use") in the morning hours, but mostly white diagnostics, which indicated correct operation.

All the required data for the OAE module appears to be available from the control-system sensors, indicating that the sensors are functioning.

Some caution should be exercised in reaching conclusions about proper operation of the air handlers in this building, even for air handlers showing predominately white cells during the test period. Because the WBD is a passive diagnostician, it can only detect and diagnose problems revealed by the conditions to which the air handling system is exposed during the test (data collection period). Other conditions might reveal other operation problems, not apparent during the one-week off-line test period. This presents a unique challenge for cases where a service provider may chose to collect data over a short time period (like the test period) and then process it with the WBD to identify and diagnose problems with equipment at an installation. The WBD will identify more problems (or validate proper operation) over more modes of operation if installed permanently or applied to data seasonally if used on short-term data.

8 Summary of On-line Data Collection, Testing Results and Savings Opportunities

Continuous trend-log data collection and testing started in September of 2002 and continued through the end of the demonstration project. The WBD was configured for all six air handling units at the same time as the data collection and testing started. The off-line trend log data from May 17, 2001 through May 24, 2001 was also included and reprocessed along with the new on-line data.

The diagnostic results for each air handler are shown in this section, a number of problems have been identified by the WBD on all six of air handlers in the demonstration. Although problems have been identified, corrective measures to address the problems have not been implemented. This was due to the site administrator (service provider) not having direct authority to address the correction of problems without authorization from the building management and the time required to take corrective measures prior to the end of this demonstration.

8.1 Configuring the Diagnostician

A screenshot of the configuration window of the WBD's user interface for AHU-1 at 300 Capital Mall is shown in Figure 13**.** The configuration is typical for all six of the air handlers (AHU-1 through AHU-6) with the exception of individual air handler supply airflow rates, which are related to the size of the air handlers. The left side is the hierarchical "configuration tree," specified by the Administrator for a given WBD installation. In this case there is the 300 Capital Mall building and a data collection network at the highest level. Beneath the building designation (Capitol Mall) in the tree is a heating/cooling plant (CM Plant), which serves the air handlers. When the user selects AHU-1 in the configuration tree by pushing the configuration button on the toolbar, AHU-1's configuration is displayed as shown in Figure 13.

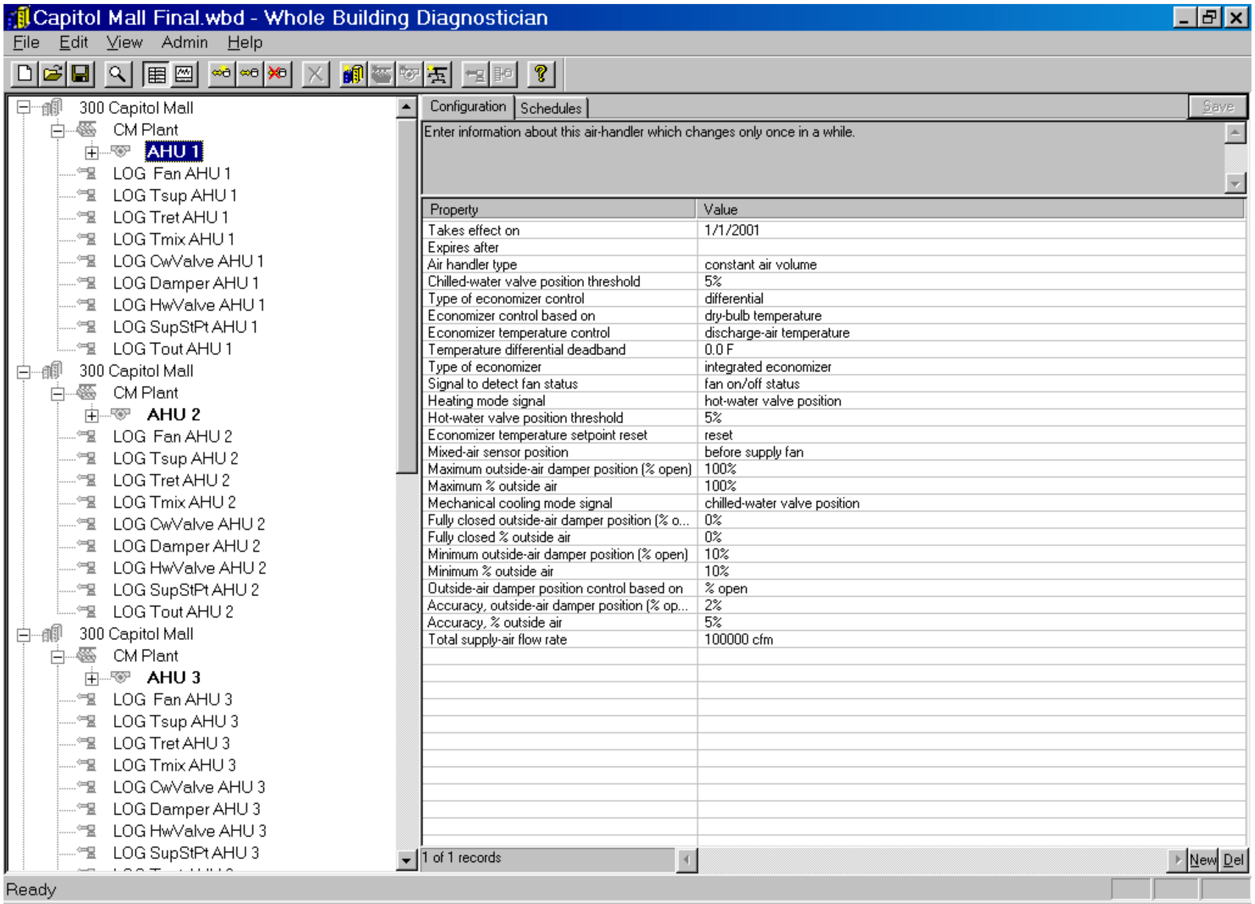

Figure 13 – Typical On-line Air Handler Configuration Screen (AHU-1 shown)

8.2 Data Collection

The WBD's automated on-line data collection module uses the Dynamic Data Exchange (DDE) protocol, an industry standard protocol developed by Microsoft, for exchanging data between two applications. The American Auto-Matrix control system that is deployed at 300 Capitol Mall, however, had no support for the DDE protocol, but supported the BACnet protocol through a Gateway device as shown in Figure 14. Therefore, the WBD's data collection module was modified to access data through the BACnet gateway. The modified data collection module was successfully tested in the laboratory before it was deployed at 300 Capitol Mall. The schematic of the deployment is shown in Figure 14. The WBD, using the custom driver (identified in the figure as Battelle's BACnet driver), communicated with the Sage BACnet Gateway through a third-party software library (BACDoor Client from Polarsoft).

Initially there were some timing issues between Battelle's drivers, Polarsoft library and the gateway; making sure the time delays between the modules and the gateway were synchronized solved these issues. Even after these issues were resolved, the gateway did not provide data consistently. More importantly, the gateway would crash after some time. Both the Polarsoft and Battelle staff did not think the crash was a result of the data requested, but it was related to the gateway. We could not get the hardware manufacture to resolve the problems in a timely manner. Therefore, the data from the trend logs was processed periodically offline using the

WBD's data collection module. The 5-minute interval data from the trend logs was integrated over the hour before being processed by the diagnostic module.

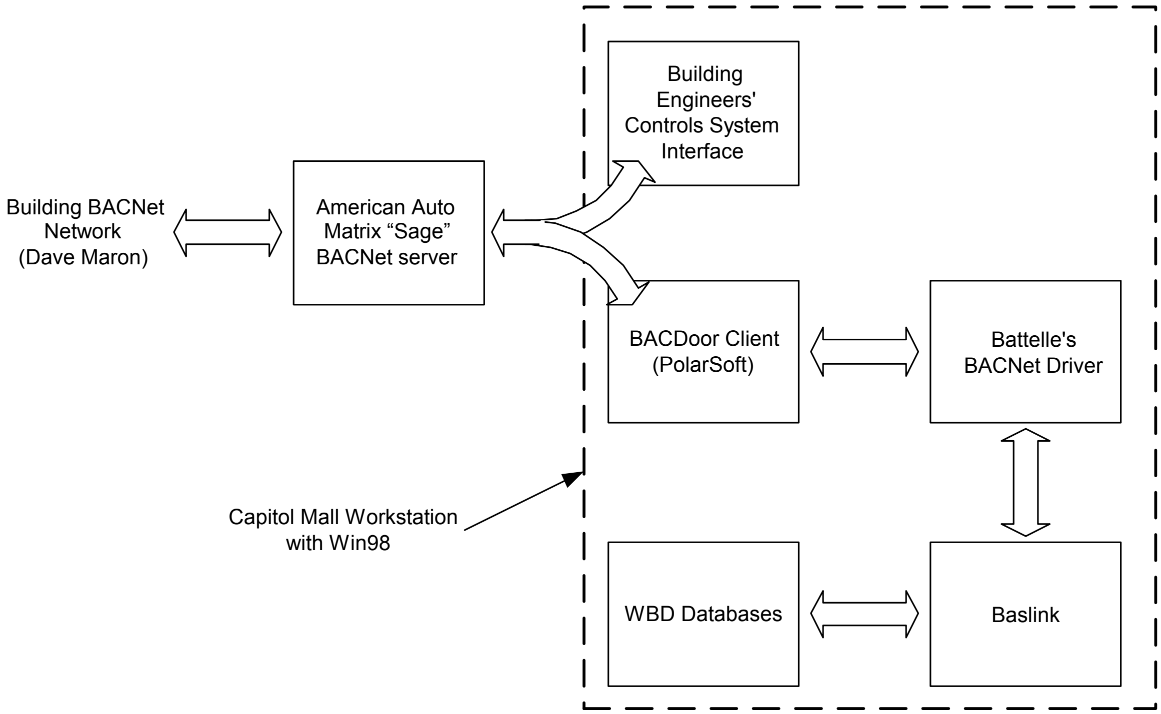

Figure 14 – Schematic diagram of the On-line Data Collection Process at Capitol Mall

The list of data points for each of the six AHUs at the 300 Capitol Mall is shown in Table 4. Integration of most channels is conditioned on whether the fan is on, as shown in Table 4. As noted earlier, the automated on-line data collection started in September 2002 for all six AHUs.

Table 4 – Data Points Collected by Capitol Mall for OAE Diagnostic Module

Type of Data	Data Item	Units	Integration
time stamp	time stamp (end of hour)	Date Time	None
fan on-time	fan on-time	Fraction	average hourly
air temperatures	outdoor-air (dry-bulb) temperature	°F	average hourly when fan on
	return-air (dry-bulb) temperature		
	mixed-air (dry-bulb) temperature		
	supply-air temperature (dry-bulb)		
control set points	Supply air set point	°F	average hourly when fan on
damper position	outdoor-air damper position command	% open	average hourly when fan on
status of AHU	chilled-water valve position (fraction open)	% open	average hourly when fan on
	hot water valve position (fraction open)		

8.3 Results for AHU-1

Initially, when the off-line data from AHU-1 were processed most of the cells were red and yellow during the occupied hours; see off-line results in Figure 10**.** The on-line diagnostics screen in Figure 15 displays red cells as indicating energy waste. The red cells throughout the on-line monitoring period are primarily indicating a damper position problem – i.e., the damper is not being fully opened during economizer operations as shown in the *Current Conditions* dialog in Figure 16 (the other cause in Figure 16 is not applicable because the configuration of supply-air set point was verified to be correct).

On further investigation by clicking on the Details button the *Details* Dialogue screen appears, as shown in Figure 17. It further confirms the primary cause that the damper is not fully open during economizer operation. Based on the current conditions, the mixed-air temperature (73.4°F) should be nearly equal to outdoor-air temperature (66.2°F), but it is not. More recent results also show a similar pattern as shown in Figure 18.

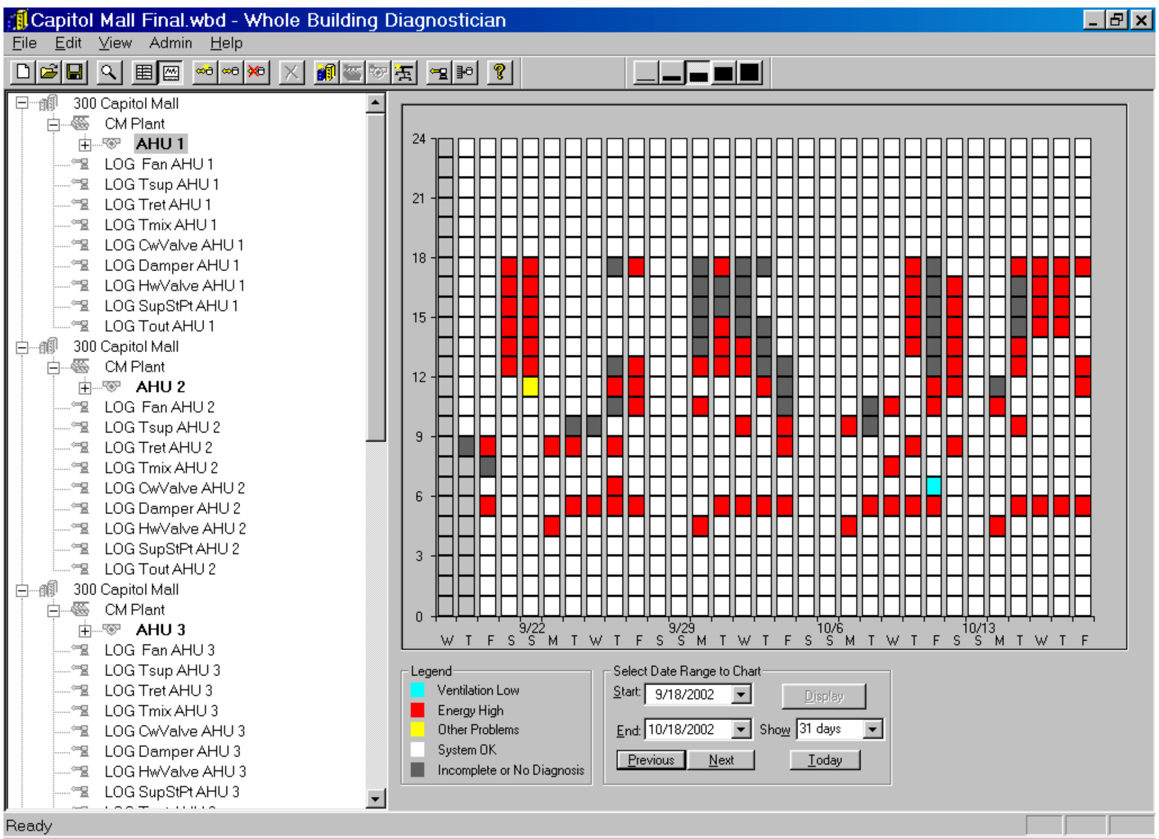

Figure 15 – WBD On-line Diagnostic Results for AHU-1 for a Period from September 19, 2002 through October 18, 2002

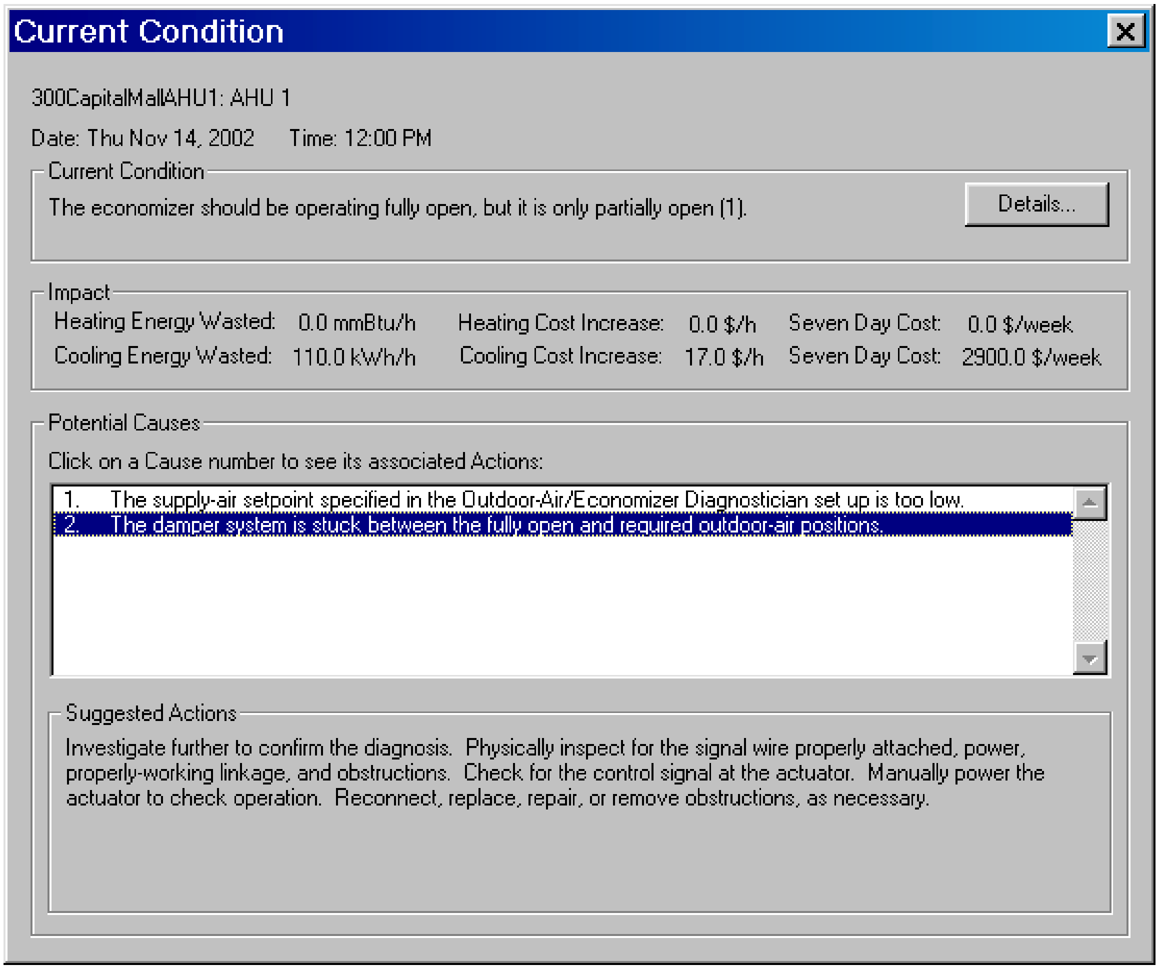

Figure 16 – Current Conditions Dialogue for AHU-1 for November 14, 2002 at 12:00 pm, Indicating a Damper Positioning Problem

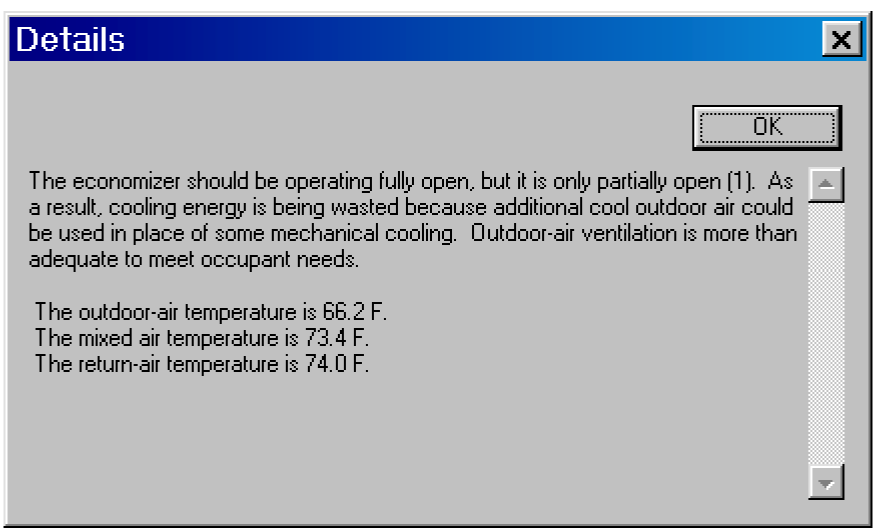

Figure 17 – Details Dialogue for AHU-1 for November 14, 2002 at 12:00 pm, Indicating a Damper Positioning Problem

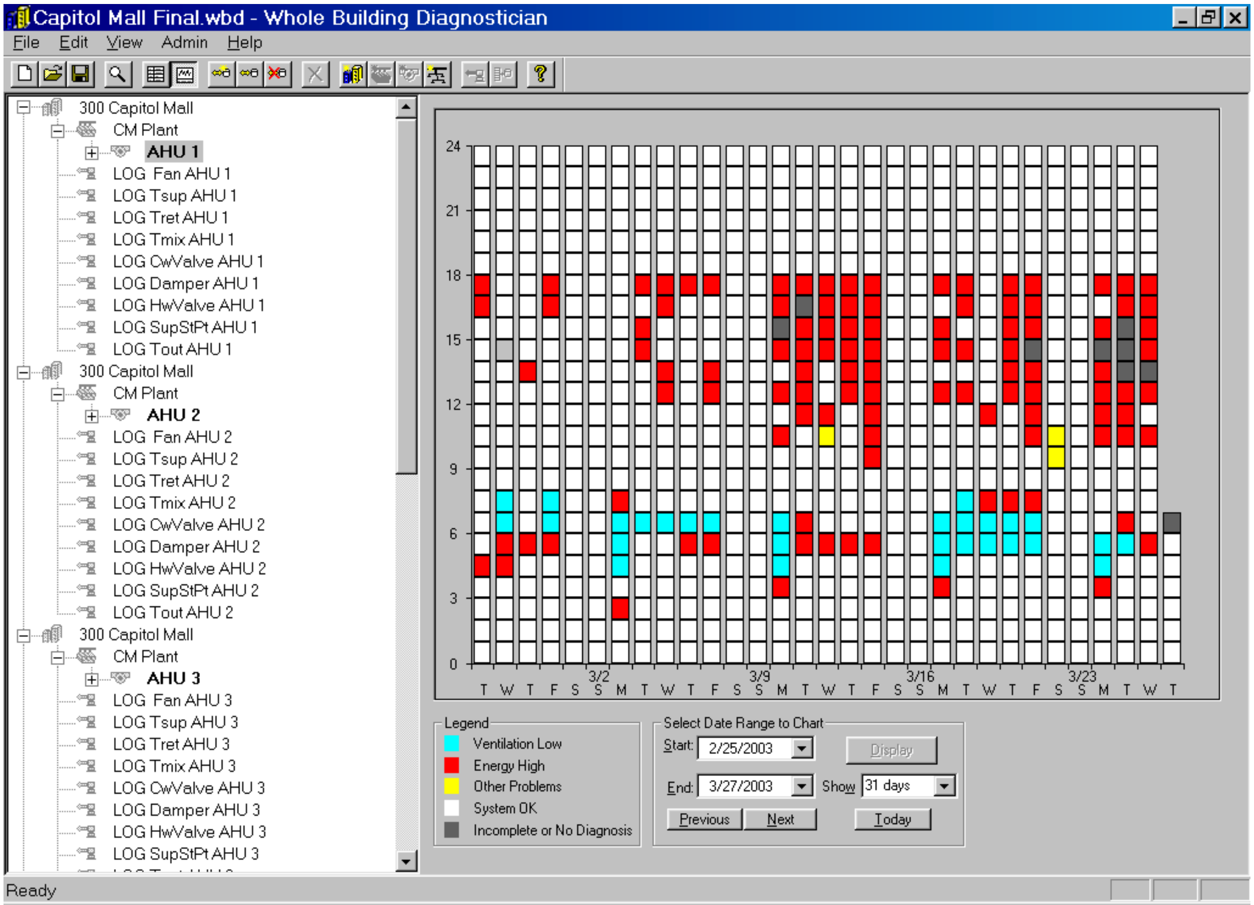

Figure 18 – WBD On-line Diagnostic Results for AHU-1 for a Period from February 25, 2003 through February 27, 2003

The frequency of problems reported for AHU-1 is shown in Table 5. AHU-1 operates 8% of the occupied period with a control problem, 8% with excess ventilation, 8% with inadequate ventilation and 15% with low economizer flow (economizer not fully open).

Table 5 – Frequency of the Problems for AHU-1 when the Supply-Fan was Operational (one week in May 2001 and September 2002 through March 2003)

Category of Operational States	Average Reliability Score	Number of Occurrences	Percent of Total Hours (%)
Control Problem	0.935	20	1.2
Control Problem - Excess Energy	0.898	116	6.9
Excess Ventilation	0.850	135	8.1
Low Economizer Flow	0.876	252	15.1
Inadequate Ventilation	0.850	135	8.1
OK but incomplete	0.751	56	3.4
Operation OK	0.832	956	57.2
Total		**1670**	**100**

8.4 Results for AHU-2

The results from the WBD indicate that like AHU-1, AHU-2 is also operating improperly as seen from the most current screenshot of the processed results in Figure 19. A significant number of the cells during occupied hours (5 a.m. to 6 p.m.) are red, followed in frequency by blue and gray. The red cells indicate energy waste; the blue cells, in most cases, indicate a problem with the temperature sensors (outdoor-air, return-air or mixed-air) or low ventilation.

Clicking on one of the red cells (hour 12:00 pm on March 10, 2003) displays the *Current Conditions Dialogue,* shown in Figure 20. The dialogue indicates, "The economizer should be fully open but is only partially open" and gives a list of potential causes. By browsing the other red cells in the monitoring period, this message was found to be common. Clicking on the *Details* button provides additional information on the nature of the problem, as shown in Figure 21. This provides a more detailed description of the problem and some key data upon which detection of the problem is based. Review of the measured data can also help understand the problem better. The mixed-air temperature (70.1^{o}F) should be equal to the outdoor-air temperature (67.3^{o}F) but is closer to the return-air temperature (72.9^{o}F), which would indicate the damper is not fully open. Although the OAE diagnostician has detected potential causes, it cannot isolate the exact problem. Examination of the OAE hourly data, as shown in Figure 22, however, has indicated the outdoor-air damper is 63% open, during this period. Based on the outdoor-air temperature being lower than the return-air temperature and the supply-air set point of 66.3^{o}F, the damper should be fully open. Upon further investigation of other red cells and associated hourly data the same damper positioning problem exists.

Clicking on one of the blue cells (hour 7:00 am on March 25, 2003) displays the *Current Conditions Dialogue,* shown in Figure 23. The dialogue indicates, "Inadequate outdoor-air ventilation is being supplied" and gives a list of potential causes. By browsing the other blue cells during the hours of 6:00 am and 7:00 am, this message was found to be common. Clicking on the *Details* button provides additional information on the nature of the problem, as shown in Figure 24. This provides a more detailed description of the problem, and some key data upon which detection of the problem is based. This data can also help understand the problem better. Although the OAE diagnostician has detected a problem with the low ventilation, it cannot isolate the exact problem.

Examination of the OAE hourly data, as shown in Figure 25**,** however, has indicated the outdoor-air damper is in the closed position, during this occupied period. Upon further investigation of other blue cells and associated hourly data, the same damper positioning problem exists and is most prevalent during a morning warm-up cycle.

Another problem also related to outdoor-air damper positions occurs during the heating mode. For several hours during heating mode operation, AHU-2 is drawing more than the minimum ventilation rate, which increases the heating energy consumption.

The frequency of problems reported for AHU-2 is shown in Table 6. AHU-2 operates 6% of the occupied period with a control problem, 17% with excess ventilation, 11% with inadequate ventilation and 11% with low economizer flow (economizer not fully open).

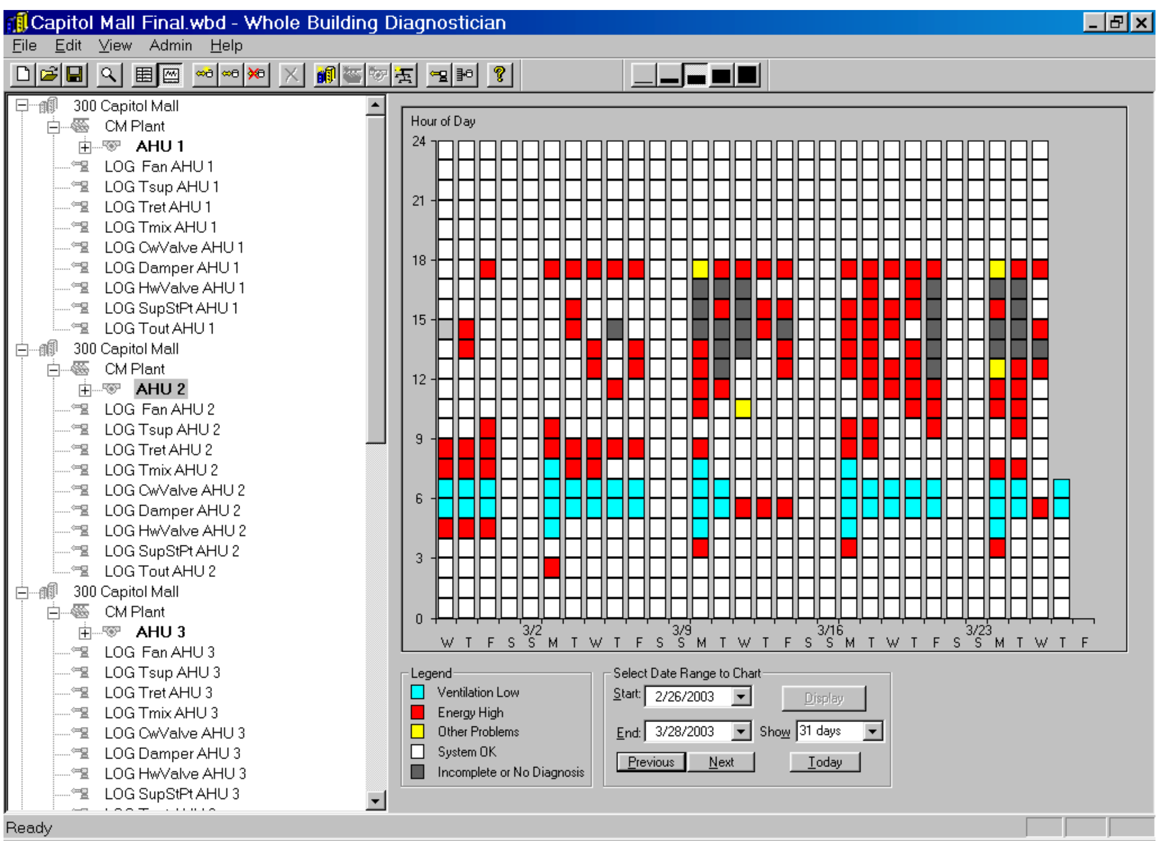

Figure 19 – WBD On-line Diagnostic Results for AHU-2 for a Period from February 25, 2003 through March 28, 2003

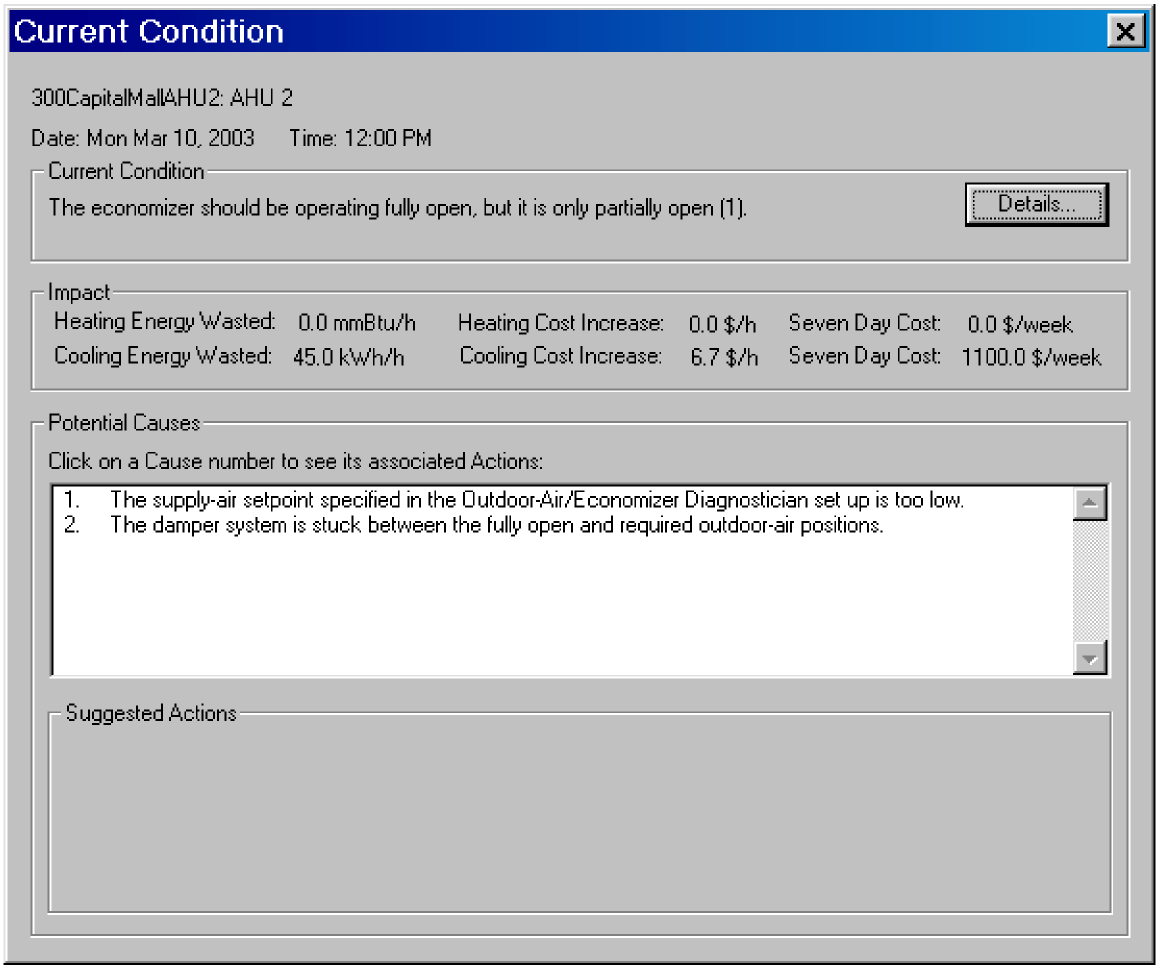

Figure 20 – Current Conditions Dialogue for AHU-2 for March 10, 2003 at 12:00 pm

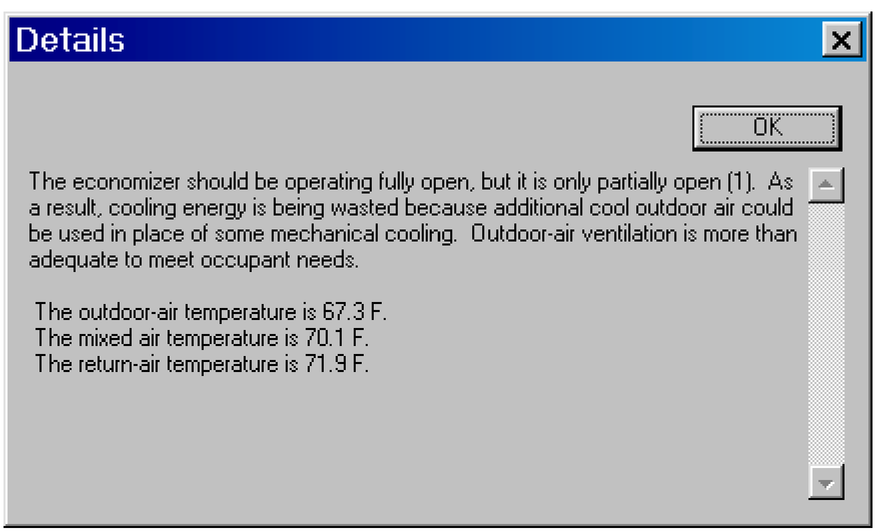

Figure 21 – Details Dialogue for AHU-2 for March 10, 2003 at 12:00 pm

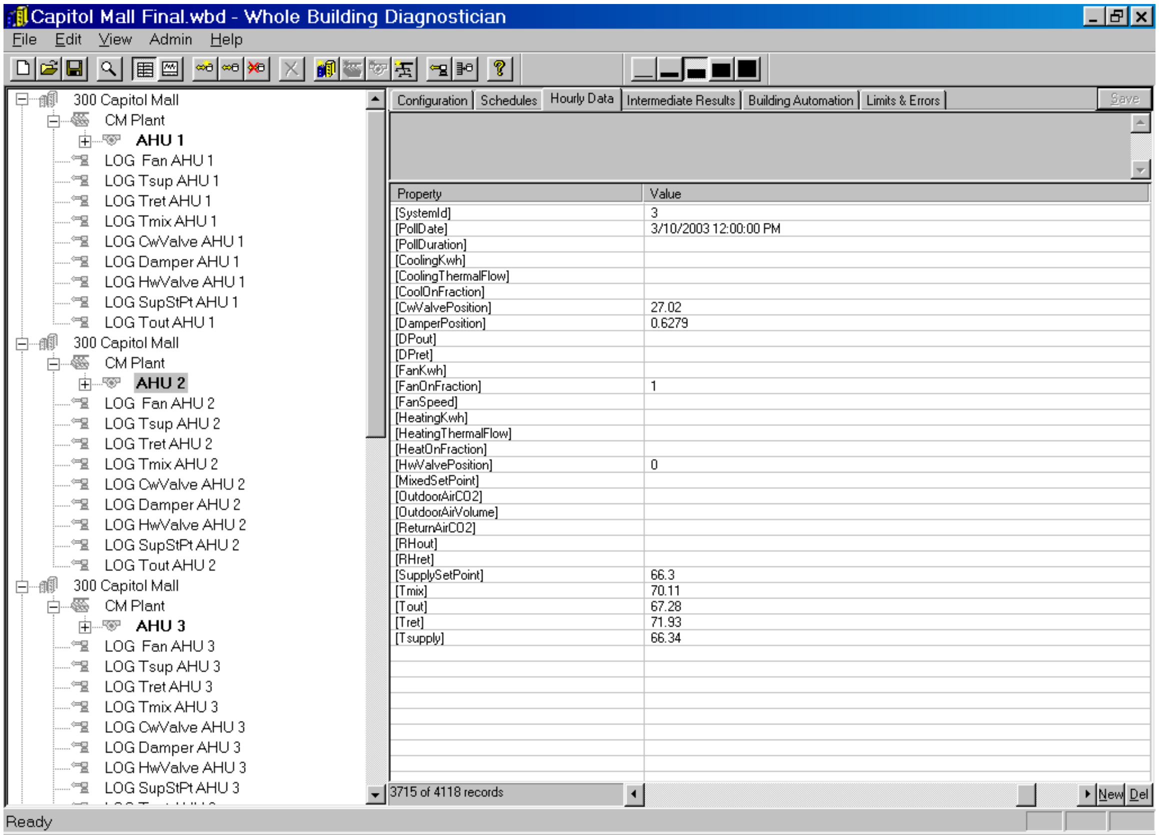

Figure 22– Hourly Data for AHU-2 for March 10 2003 at 12:00 pm

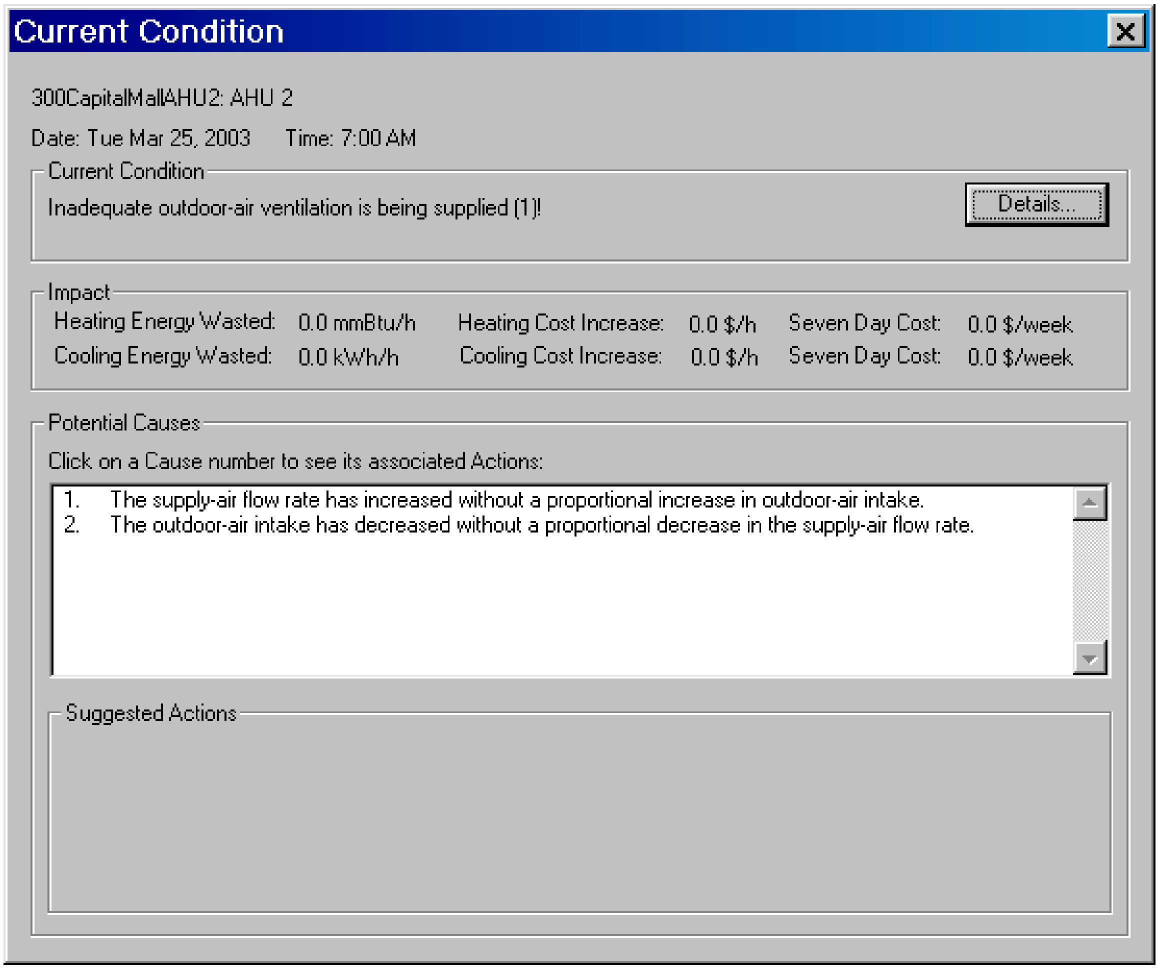

Figure 23 – Current Conditions Dialogue for AHU-2 for March 25, 2003 at 7:00 am

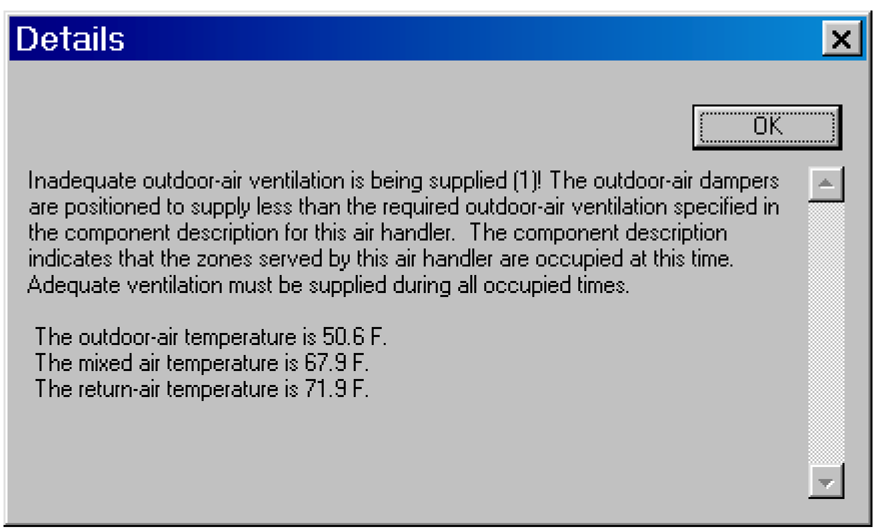

Figure 24 – Details Dialogue for AHU-2 for March 25, 2003 at 7:00 am

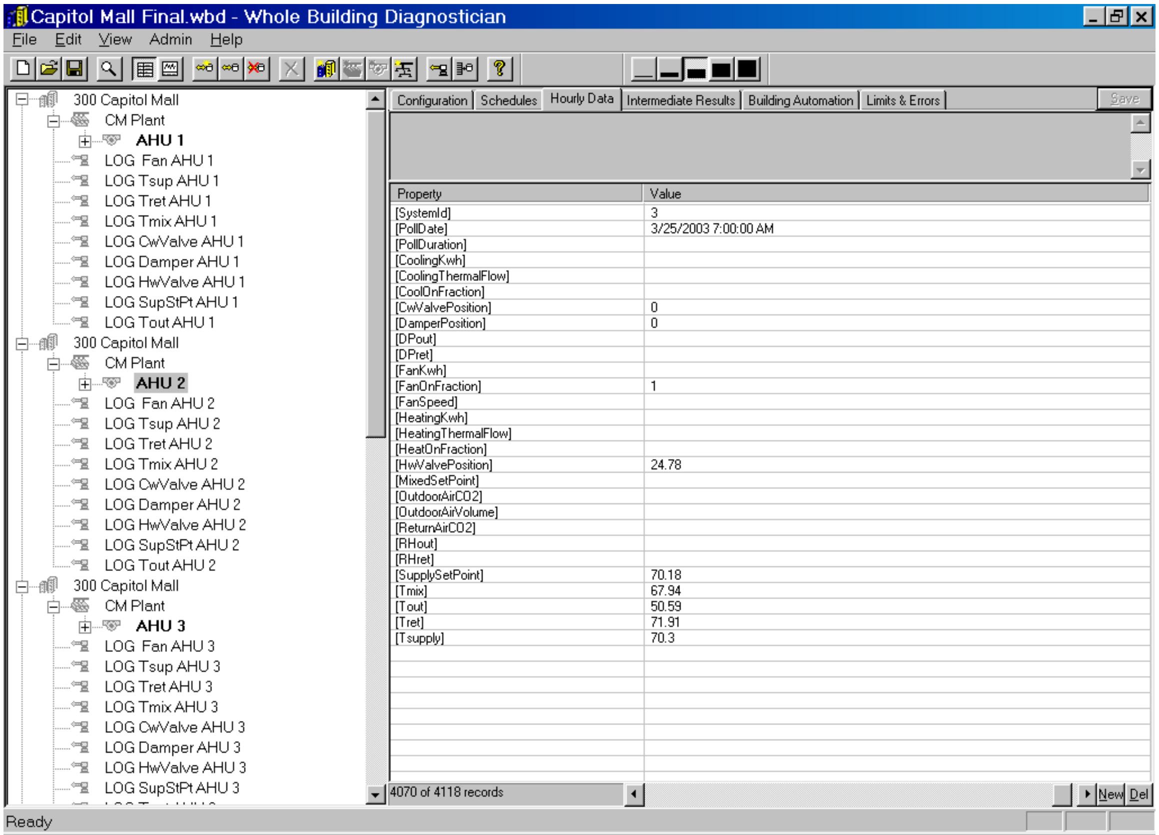

Figure 25 – Hourly Data for AHU-2 for March 25, 2003 at 7:00 am

Table 6 – Frequency of the Problems for AHU-2 when the Supply-Fan was Operational (a week in May 2001 and September 2002 through March 2003)

Category of Operational States	Average Reliability Score	Number of Occurrences	Percent of Total Hours (%)
Control Problem	0.933	10	0.6
Control Problem - Excess Energy	0.878	91	5.3
Excess Ventilation	0.897	295	17.2
Low Economizer Flow	0.892	181	10.5
Inadequate Ventilation	0.856	191	11.1
OK but incomplete	0.709	92	5.4
Operation OK	0.811	857	49.9
Total		**1717**	**100**

8.5 Results for AHU-3

The results from the WBD indicate that like AHU-1 and AHU-2, AHU-3 is operating improperly as well. The screenshot of the processed results for the time period between February 28 and March 27, 2003 (most current), is shown in Figure 26. A significant number of the cells during occupied hours (5 a.m. to 6 p.m.) are blue, followed in frequency by red cells and a few gray cells. Blue cells, in most cases, indicate a problem with the temperature sensors (outdoor-air, return-air or mixed-air) or low ventilation. Clicking on one of the blue cells (hour 12 on March

24, 2003) displays the *Current Conditions Dialogue,* shown in Figure 27. The dialogue indicates, "Inadequate outdoor-air ventilation is being supplied" and gives you a list of potential causes. By browsing the other blue cells, this message was found to be common.

Clicking on the *Details* button provides additional information on the nature of the problem, as shown in Figure 28. This provides a more detailed description of the problem, and some key data upon which detection of the problem is based. This data can also help the user understand the problem better. The mixed-air temperature (71.3^{o}F) is almost equal to the return-air temperature of (71.6^{o}F) with the outdoor-air temperature reading at 68.8^{o}F, which would indicate the outdoor-air damper is closed. Although the OAE diagnostician has detected a problem with low ventilation, it cannot isolate the exact problem.

Examination of the OAE hourly data, as shown in Figure 29**,** however, has indicated the outdoor-air damper is in the closed position, during this occupied period. Upon further investigation of other blue cells and associated hourly data the same damper positioning problem is found to exist and is most probably a ventilation-scheduling problem. The red cells during the monitoring period also indicate a damper positioning problem during economizing and heating modes. During the periods when it is favorable for economizing, the outdoor-air damper is not fully open and during the heating mode excess ventilation is being provided. Both these problems are similar to the problems identified for AHU-2.

The frequency of problems reported for AHU-3 is shown in Table 7. AHU-3 operates less than 1% of the occupied period with a control problem, 14% with excess ventilation problem, 17% with inadequate ventilation and 4% with low economizer flow (economizer not fully open).

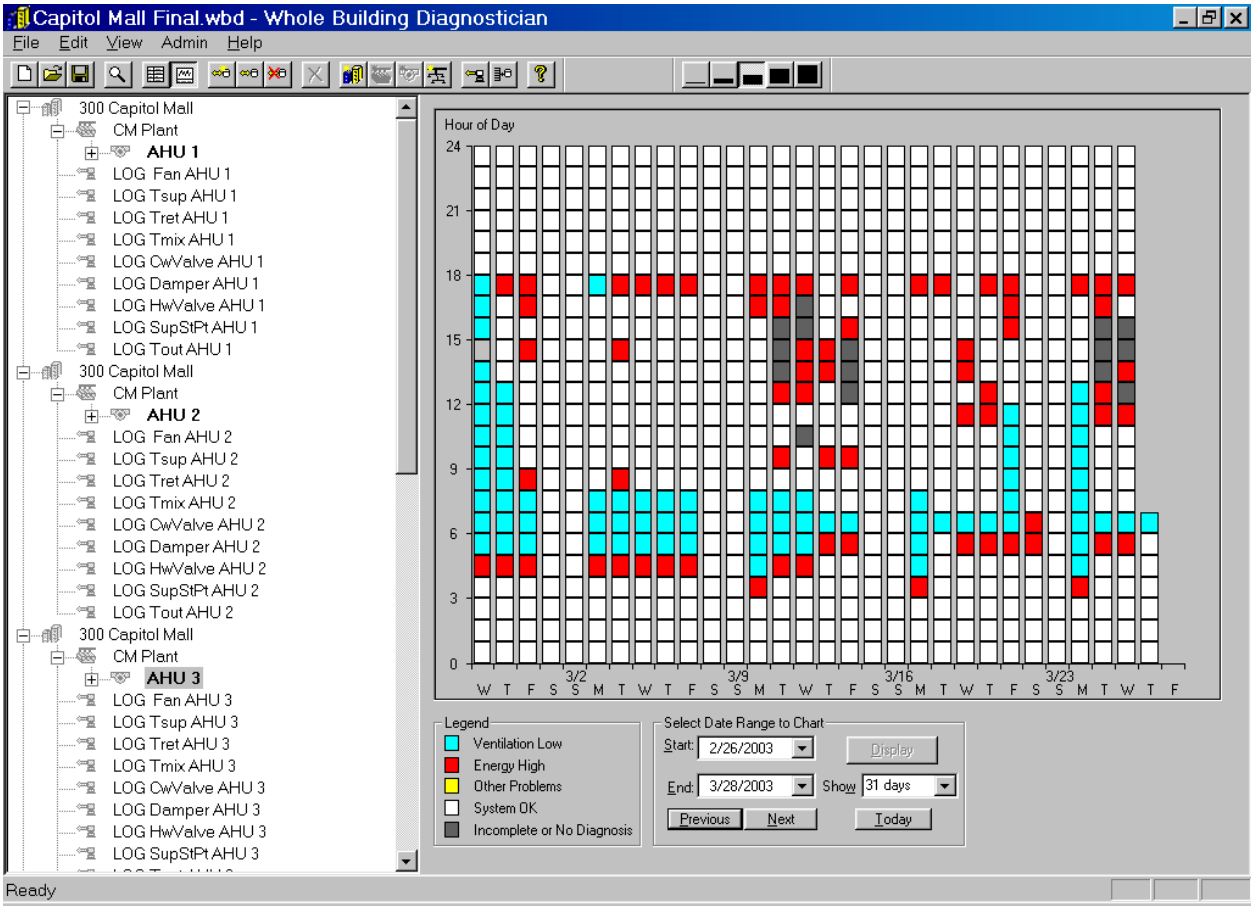

Figure 26 – WBD On-line Diagnostic Results for AHU-3 for a Period from February 26, 2003 through March 27, 2003

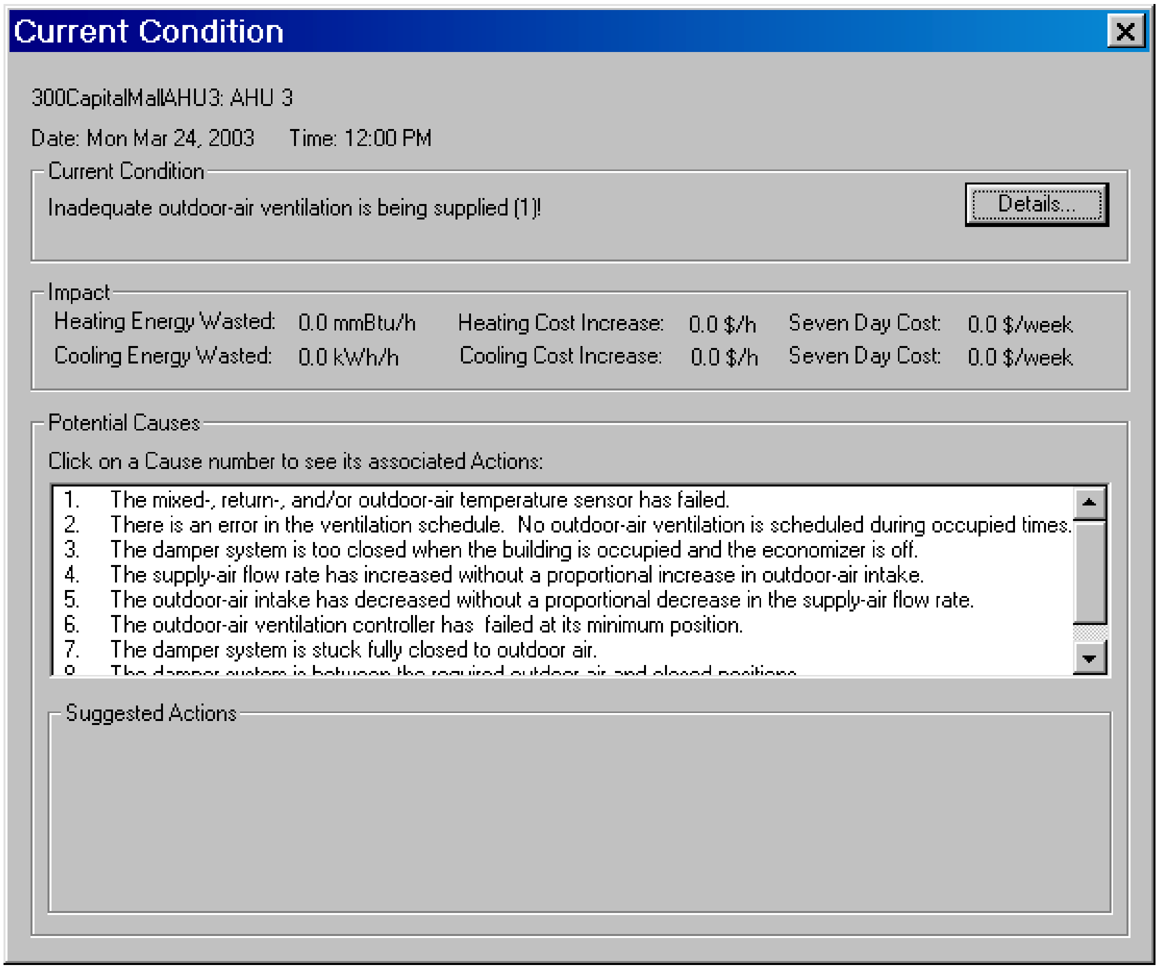

Figure 27 – Current Conditions Dialogue for AHU-3 for March 24, 2003 at 12:00 pm, Indicating a Inadequate Ventilation Problem

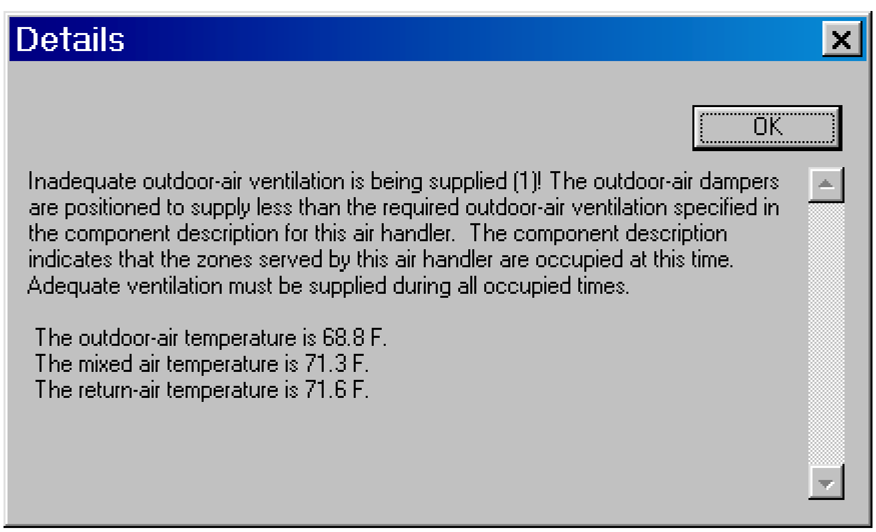

Figure 28 – Details Dialogue for AHU-3 for March 24, 2003 at 12:00 p.m., Indicating Inadequate Ventilation Problem

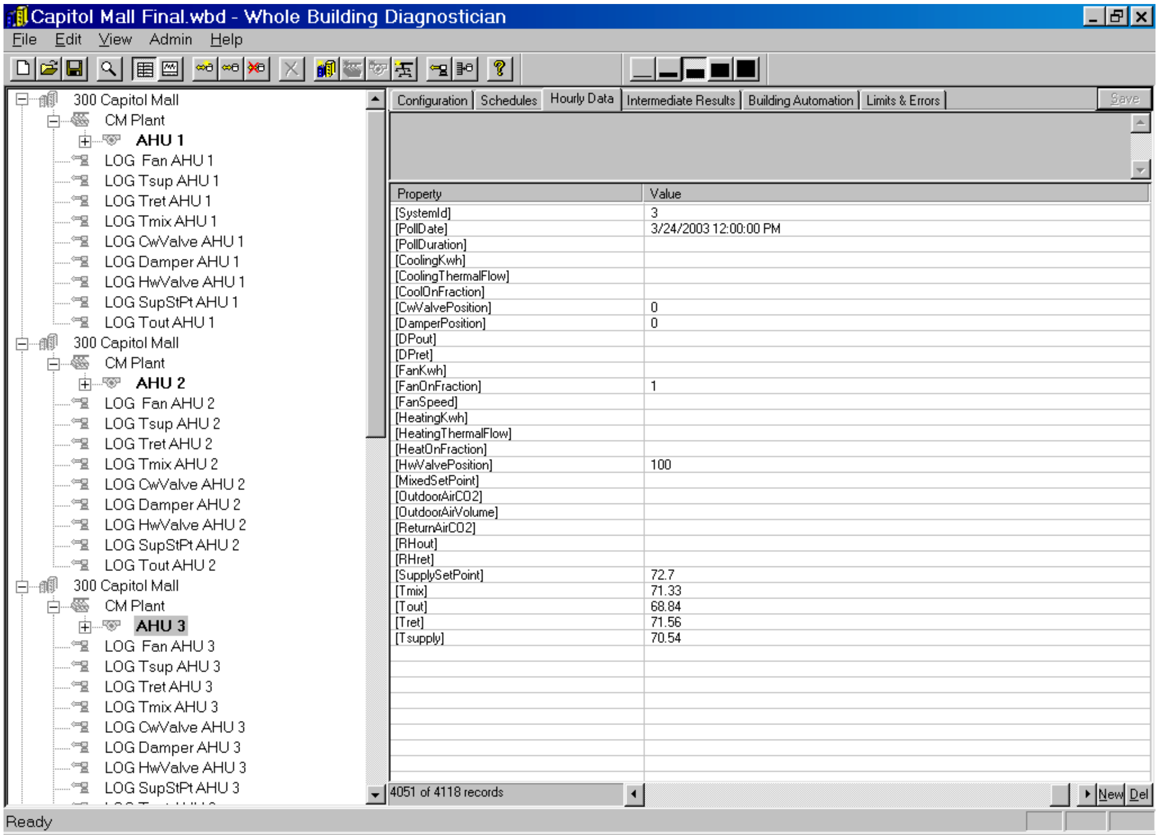

Figure 29 – Hourly Data for AHU-3 for March 24, 2003 at 12:00 pm, Indicating Inadequate Ventilation Problem

Table 7 – Frequency of the Problems for AHU-3 when the Supply-Fan was Operational (a week in May 2001 and September 2002 through March 2003)

Category of Operational States	Average Reliability Score	Number of Occurrences	Percent of Total Hours (%)
Control Problem	0.962	7	0.4
Control Problem - Excess Energy	0.870	8	0.5
Excess Ventilation	0.853	240	14.2
Low Economizer Flow	0.858	64	3.8
Inadequate Ventilation	0.857	294	17.4
OK but incomplete	0.748	67	4.0
Operation OK	0.852	1007	59.7
Total		**1687**	**100**

8.6 Results for AHU-4

The results from the WBD indicate that AHU-4, like the previous three AHUs, is being operated improperly. The screenshot of the processed results for the time period between February 21 and March 22, 2003 (most current), is shown in Figure 30. A significant number of the cells during occupied hours (5 a.m. to 9 p.m.) are blue, followed in frequency by red and gray. The blue cells, in most cases, indicate a problem with the ventilation schedule. Clicking on one of the blue cells (hour 7:00 am on March 5, 2003) displays the *Current Conditions Dialogue*, shown in Figure 31. The dialogue indicates, "Inadequate outdoor-air ventilation is being supplied" and gives a list of potential causes. By browsing the other blue cells, this message was found to be common.

Clicking on the *Details* button provides additional information on the nature of the problem, as shown in Figure 32. This provides a more detailed description of the problem, and some key data upon which detection of the problem is based. Review of the measured data can also help the user understand the problem better. The mixed-air temperature (70.9^{o}F) is almost equal to the return-air temperature (71.6^{o}F) with the outdoor-air temperature reading at 45.4^{o}F, which would indicate the outdoor-air damper is almost closed. Although the OAE diagnostician has detected a problem with the ventilation schedule, it cannot isolate the exact problem.

Examination of the OAE hourly data, as shown in Figure 33, however has indicated the outdoor-air damper is almost in the closed position, during this occupied period. Upon further investigation of other blue cells and associated hourly data, the same problem is found to exist and is most probably a ventilation-scheduling problem. The red cells during the monitoring period also indicate a damper positioning problem.

The frequency of problems reported for AHU-4 is shown in Table 8. AHU-4 operates 2% of the occupied period with a control problem, 7% of time with excess ventilation problem, 17% with inadequate ventilation and 7% with low economizer flow (economizer not fully open).

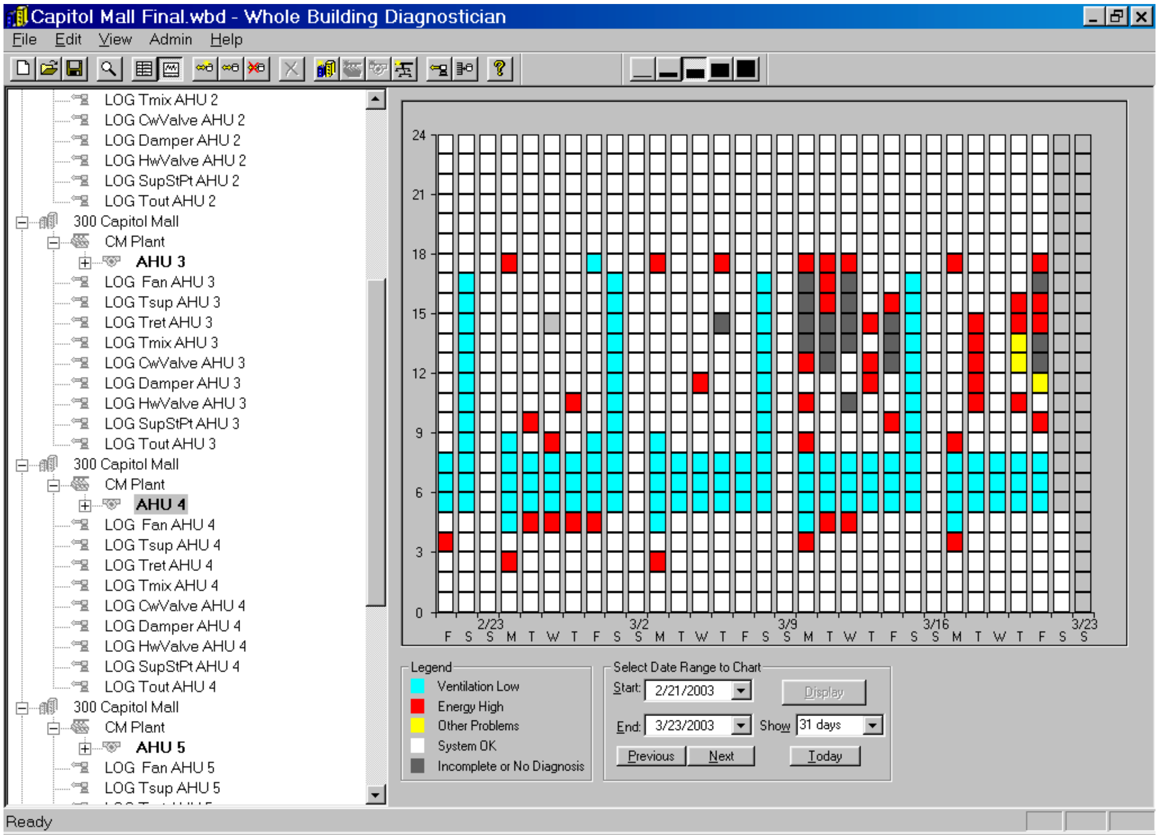

Figure 30– WBD On-line Diagnostic Results for AHU-4 for a Period from February 21, 2003 through March 22, 2003

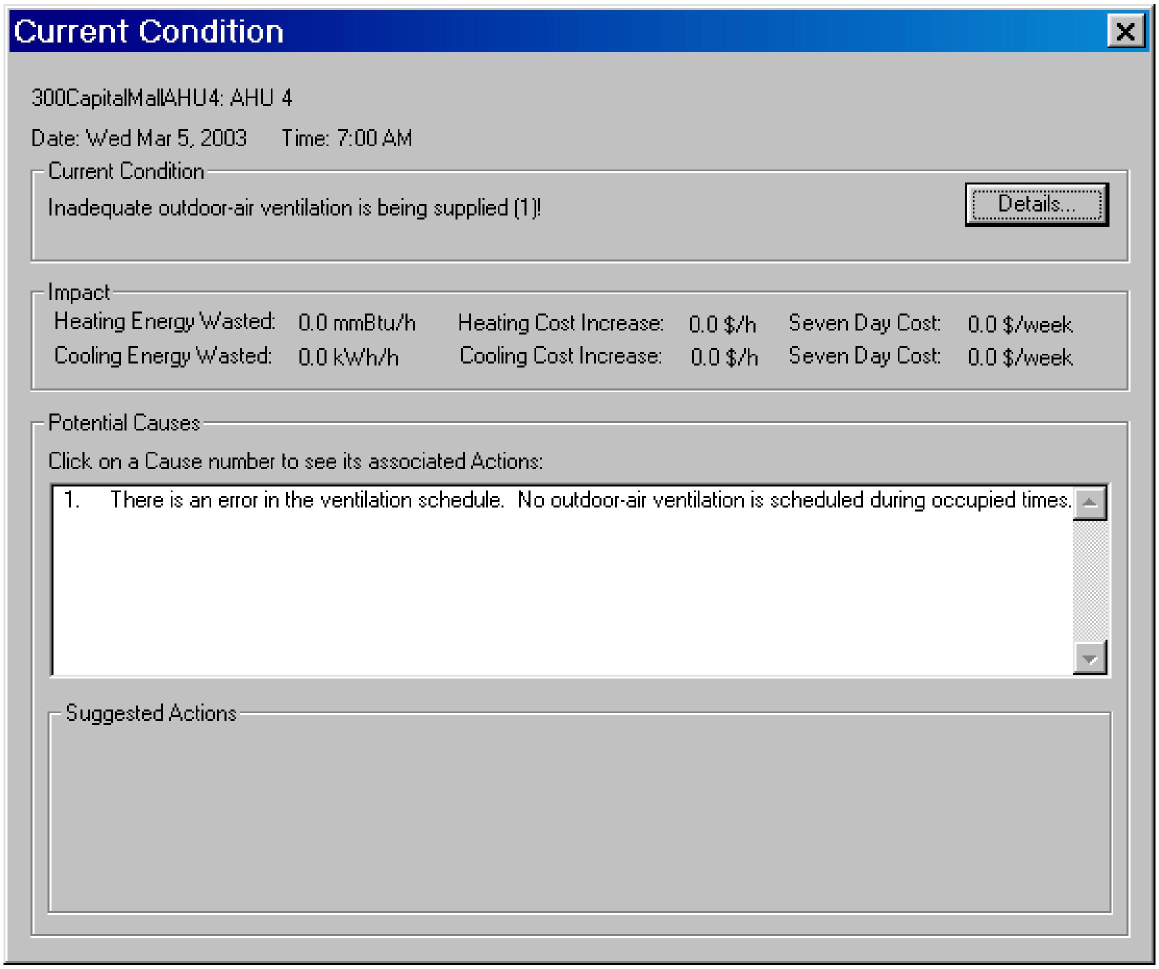

Figure 31– Current Conditions Dialogue for AHU-4 for March 5, 2003 at 7:00am, Indicating Inadequate Ventilation Problem

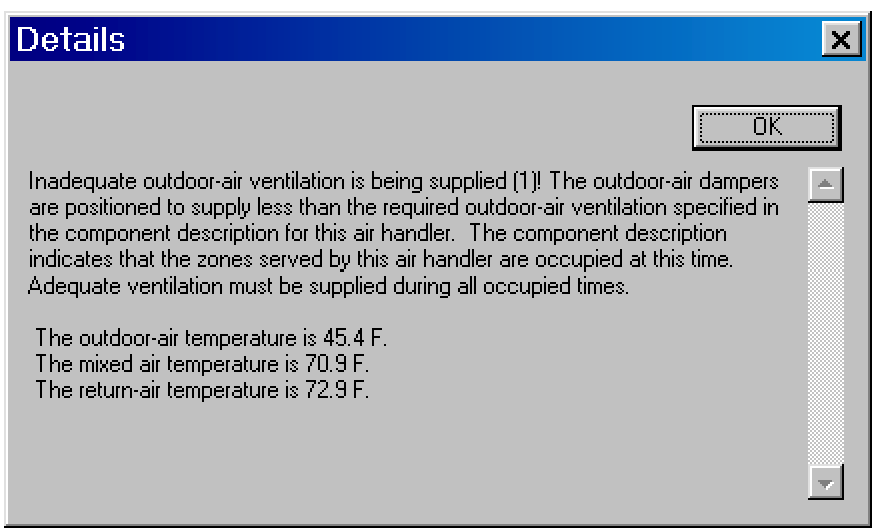

Figure 32 – Details Dialogue for AHU-4 for March 5, 2003 at 7:00 am, Indicating Inadequate Ventilation Problem

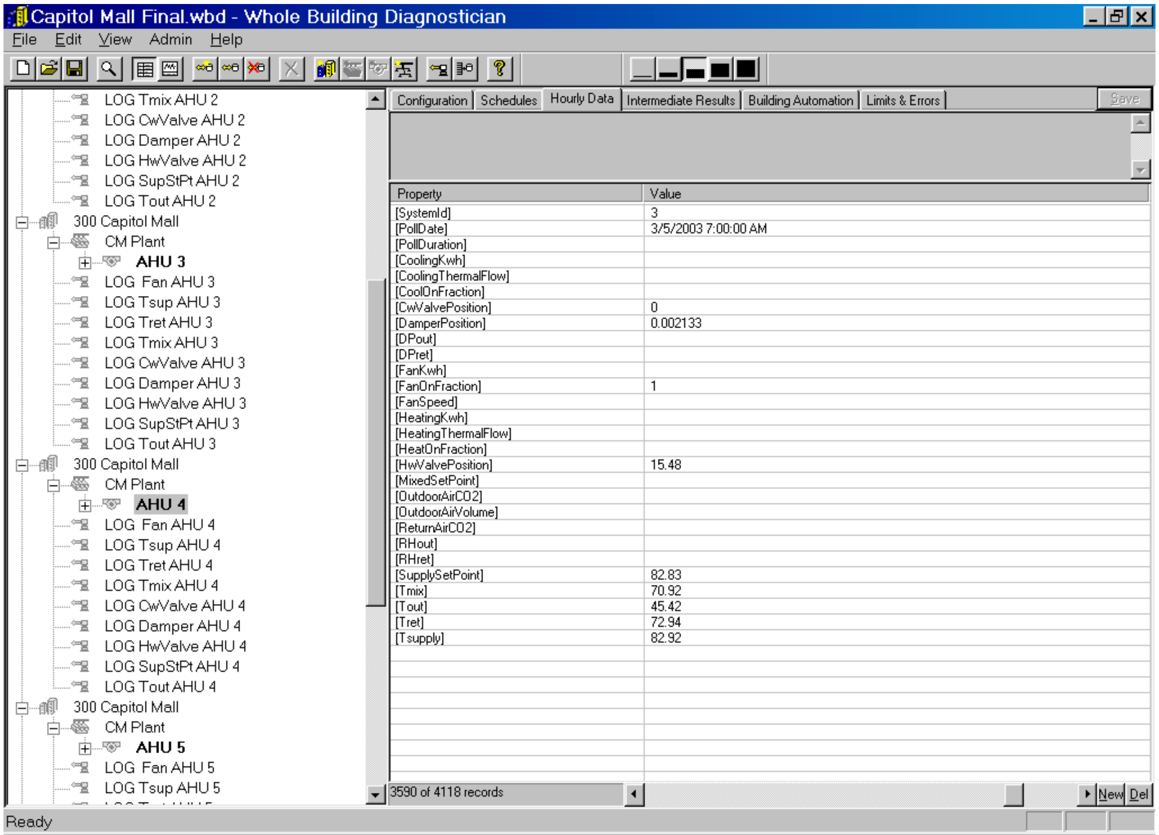

Figure 33 – Hourly Data for AHU-3 for March 24, 2003 at 12:00 p.m.

Table 8 – Frequency of the Problems for AHU-4 when the Supply-Fan was Operational (a week in May 2001 and September 2002 through March 2003)

Category of Operational States	Average Reliability Score	Number of Occurrences	Percent of Total Hours (%)
Control Problem	0.927	4	0.2
Control Problem - Excess Energy	0.885	37	2.1
Excess Ventilation	0.845	126	7.3
Low Economizer Flow	0.852	119	6.9
Inadequate Ventilation	0.851	285	16.5
OK but incomplete	0.685	120	7.0
Operation OK	0.813	1035	60.0
Total		**1726**	**100**

8.7 Results for AHU-5

The results from the WBD indicate that AHU-5, like the previous four AHUs, is being operated improperly. The screenshot of the processed results for the time period between February 26 and March 27, 2003 (most current), is shown in Figure 34. A significant number of the cells during occupied hours (5 a.m. to 9 p.m.) are red, followed in frequency by blue and a few yellow. The red cells indicate energy waste with the yellow and blue cells, in most cases, indicating a problem with the temperature sensors (outdoor-air, return-air or mixed-air). Clicking on one of the red cell (hour 5:00 pm on March 10, 2003) displays the *Current Conditions Dialogue* shown in Figure 35. The dialogue indicates, “The economizer should be fully open but is only partially open” and gives a list of potential causes. By browsing the other red cells in the monitoring period, this message was found to be common.

Clicking on the *Details* button provides additional information on the nature of the problem, as shown in Figure 36. This provides a more detailed description of the problem, and some key data upon which detection of the problem is based. Review of the measured data can also help the user understand the problem better. The mixed-air temperature (71.8^{o}F) is closer to the return-air temperature (73.4^{o}F) than the outdoor-air temperature (69.9^{o}F) indicating that the damper may not be fully open. Although the OAE diagnostician has detected four potential causes, it cannot isolate the exact problem.

Examination of the OAE hourly data, as shown in Figure 37**,** however, has indicated the outdoor-air damper is 67% open, during this period. Based on the outdoor-air temperature being lower than the return-air temperature, the outdoor-air damper should be fully open under these conditions. Upon further investigation of other red cells and associated hourly data, the same damper positioning problem is found to exist. The blue cells during the monitoring period indicate the same damper positioning problem “Inadequate outdoor-air ventilation is being supplied” similar to that of AHU-4; see Section 8.6 for explanation of this blue cell problem.

The frequency of problems reported for AHU-5 is shown in Table 9. AHU-5 operates 8% of the occupied period with a control problem, 15% of the time with excess ventilation problem, 10% with inadequate ventilation and 21% with low economizer flow (economizer not fully open).

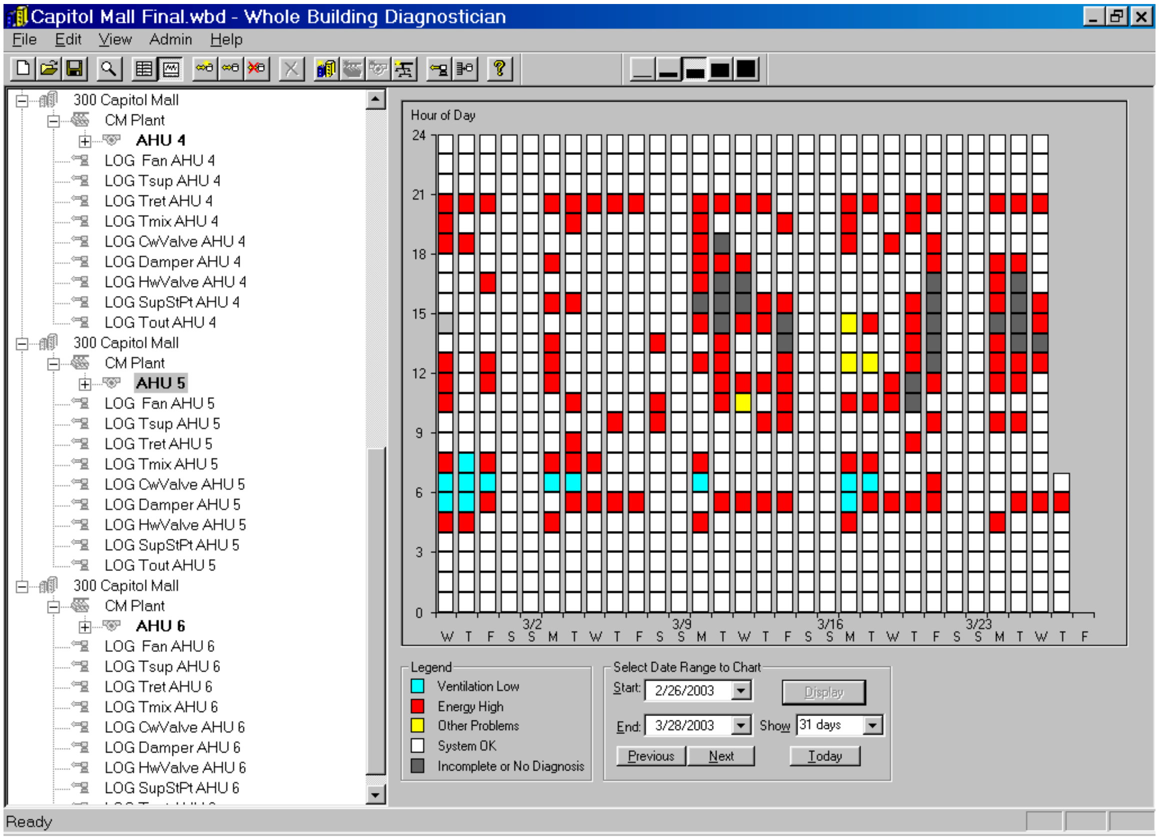

Figure 34 – WBD On-line Diagnostic Results for AHU-5 for a Period from February 26, 2003 through March 27, 2003

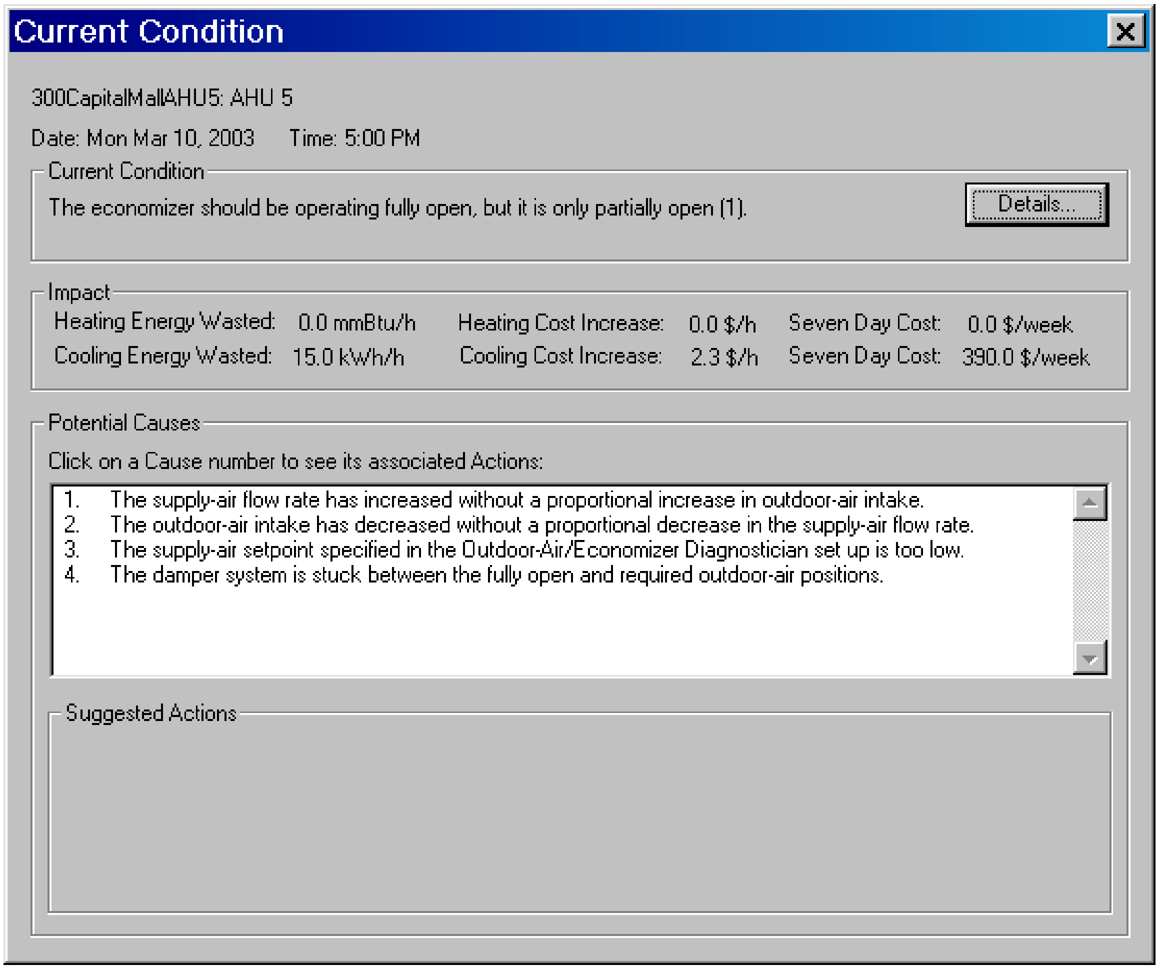

Figure 35 – Current Conditions Dialogue for AHU-5 for March 10, 2003 at 5:00 pm, Indicating Improper Economizer Operation

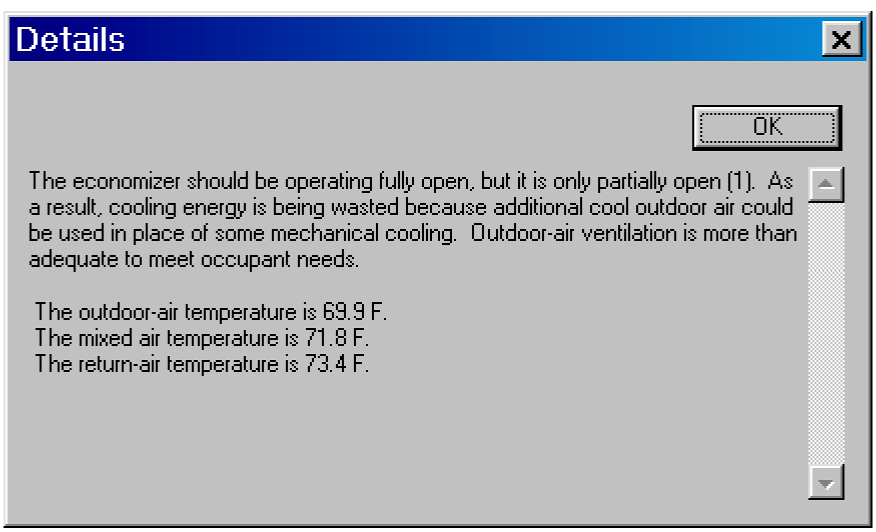

Figure 36 – Details Dialogue for AHU-5 for March 10, 2003 at 5:00 pm, Indicating an Improper Economizer Operation

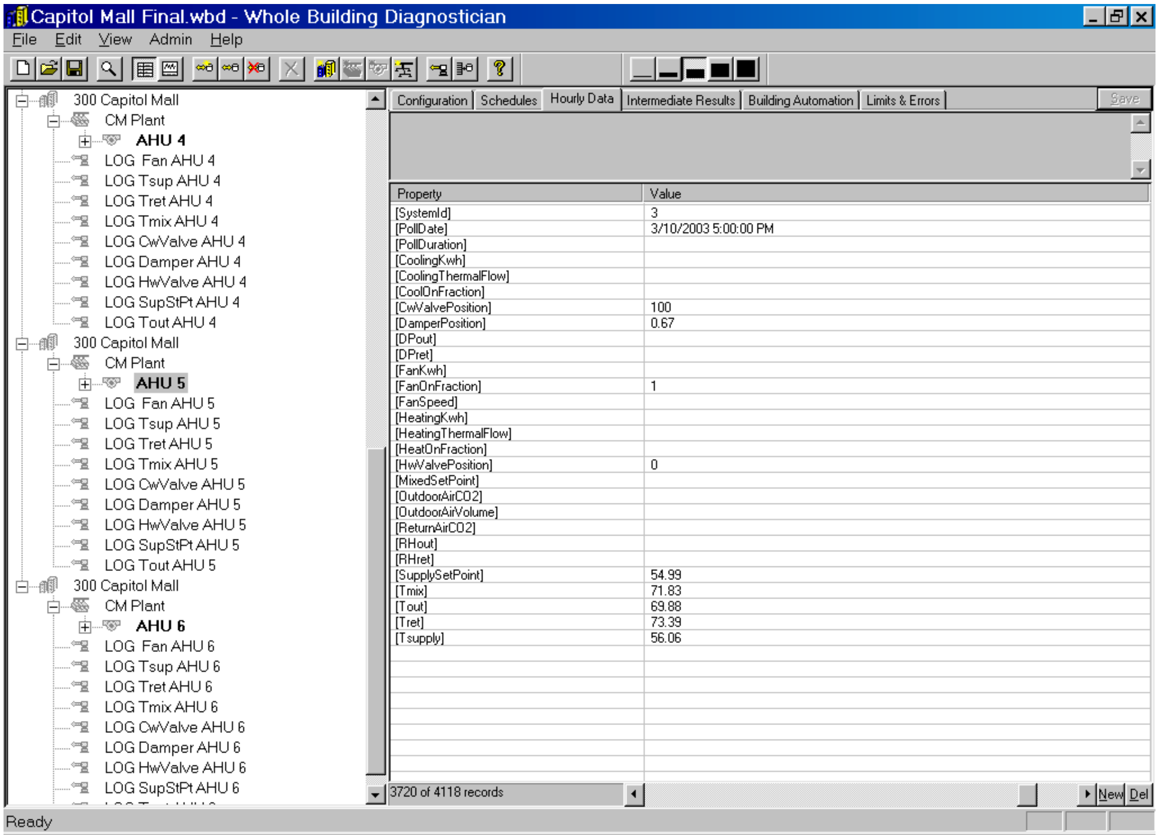

Figure 37 – Hourly Data for AHU-5 for March 10, 2003 at 5:00 p.m.

Table 9 – Frequency of the Problems for AHU-5 when the Supply-Fan was Operational (a week in May 2001 and September 2002 through March 2003)

Category of Operational States	Average Reliability Score	Number of Occurrences	Percent of Total Hours (%)
Control Problem	0.949	31	1.6
Control Problem - Excess Energy	0.933	113	5.8
Excess Ventilation	0.918	291	15.0
Low Economizer Flow	0.916	259	13.4
Inadequate Ventilation	0.884	201	10.4
OK but incomplete	0.816	411	21.3
Operation OK	0.781	628	32.5
Total		**1934**	**100**

8.8 Results for AHU-6

The results from the WBD indicate that AHU-6 is operating improperly just like the other five AHUs. The screenshot of the processed results for the time period between February 26 and March 27, 2003 (most current), is shown in Figure 38. A significant number of the cells during occupied hours (5 a.m. to 9 p.m.) are red, followed in frequency by yellow and blue. The red cells indicate energy waste with the yellow and blue cells, in most cases, indicating a problem with the temperature sensors (outdoor-air, return-air or mixed-air). Clicking on one of the red cells (hour 11:00 am on March 25, 2003), displays the *Current Conditions Dialogue* as shown in Figure 39. It indicates too much outdoor air is being provided during the heating mode and provides a list of potential causes. By browsing the other red cells in the monitoring period, this message was found to be common.

Clicking on the *Details* button provides additional information on the nature of the problem, as shown in Figure 40. This provides a more detailed description of the problem, and some key data upon which detection of the problem is based. Review of the measured data can also help the user understand the problem better. The mixed-air temperature (73.3°F) is greater than both the return-air (71.8°F) and outdoor-air (65.9°F) temperatures. Although the OAE diagnostician has detected a problem with the temperature sensors, it cannot isolate the exact problem.

The frequency of problems reported for AHU-6 is shown in Table 10. AHU-6 operates 10% of the occupied period with a control problem, 21% of the time with an excess ventilation problem, 10% with inadequate ventilation and 3% with low economizer flow (economizer not fully open).

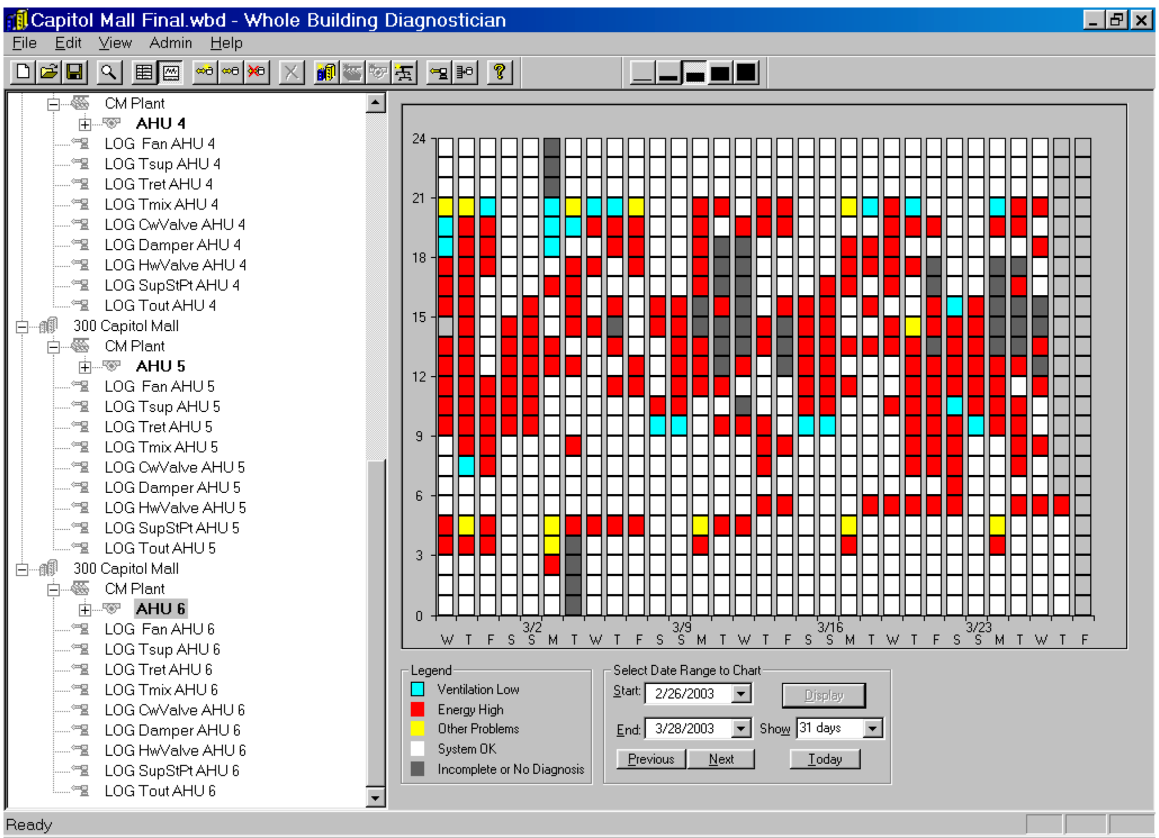

Figure 38 – WBD On-line Diagnostic Results for AHU-6 for a Period from February 26, 2003 through March 27, 2003

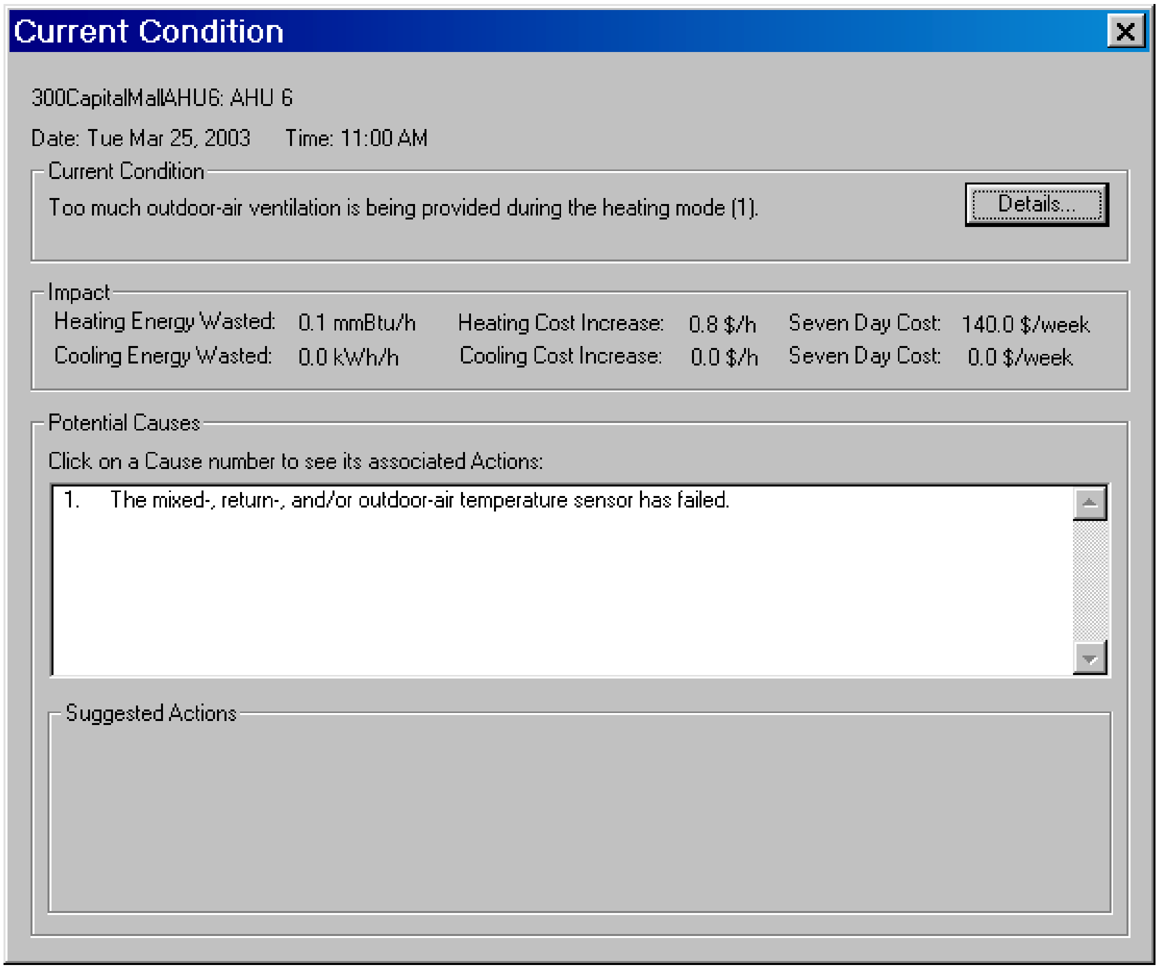

Figure 39 – Current Conditions Dialogue for AHU-6 for March 25, 2003 at 11:00am, Indicating Excess Ventilation

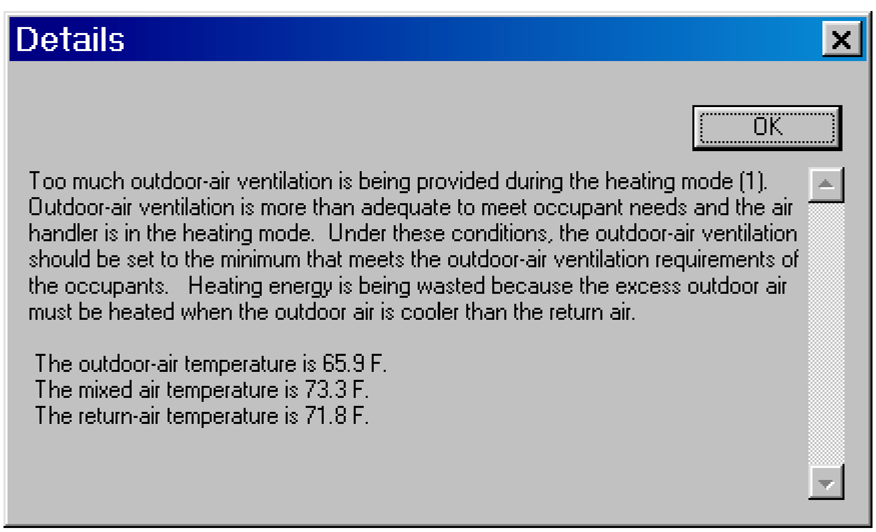

Figure 40 – Details Dialogue for AHU-6 for March 25, 2003 at 11:00 a.m. Indicating Excess Ventilation

Table 10 – Frequency of the Problems for AHU-6 when the Supply-Fan was Operational (a week May 2001 and September 2002 through March 2003)

Category of Operational States	Average Reliability Score	Number of Occurrences	Percent of Total Hours (%)
Control Problem	0.926	114	4.7
Control Problem - Excess Energy	0.883	119	4.9
Excess Ventilation	0.882	517	21.2
Low Economizer Flow	0.824	65	2.7
Inadequate Ventilation	0.899	240	9.8
OK but incomplete	0.750	235	9.6
Operation OK	0.875	1148	47.1
Total		**2438**	**100**

8.9 Saving Opportunities

Correcting the energy-wasting problems identified by the OAE will produce reductions in energy consumption and savings on energy expenditures at 300 Capitol Mall. In this section, we present the savings estimated by the OAE diagnostician from correcting the problems for all six AHUs.

A summary of problems identified and energy savings impact estimated by the OAE diagnostician are listed in Table 11. All six AHUs have problems that are related to improper operations of the outdoor-air damper. For some AHUs the damper control (positioning) problem occurs during cooling mode, for others it occurs during both cooling and heating modes. In addition, AHU-2 and AHU-4 have problem providing adequate ventilation during certain time. The service provider has confirmed all problems, but none of them have been corrected yet.

When the OAE diagnostician identifies improper operation at any given hour, it also estimates the heating or cooling energy impact by comparing the actual operation to the expected operation. Energy and cost impacts are not estimated if a temperature sensor problem exists or if the ventilation rate is inadequate. The impact estimates are based on both the measured data and user-specified inputs [e.g., the system coefficient of performance (COP) and cost of energy]. Because measured values are used in estimating the impacts, the sensors must be fault free. If the AHU has a faulty sensor (especially, the outdoor-air, return-air or mixed-air temperature), the estimates are not accurate and cannot be relied upon. After estimating the energy impact, the OAE then estimates the cost impacts using the user specified energy conversion efficiency for the heating or the cooling systems and cost of the energy. The heating and cooling system (including all auxiliary systems) efficiency and energy costs (blend cost that includes demand charges as well) are listed in Table 12.

All six AHUs at 300 Capitol Mall are VAV systems. Although the OAE can detect problems with VAV systems, the energy and cost impacts are based on the design load flow rate (or full load flow rate). Because the airflow rate in a VAV system modulates to match the load, the energy and cost impacts calculated with design flow rate are probably overestimated. A typical average fan speed (speed is proportional to air flow rate) during occupied hours in a high-rise office building with a VAV system is around 80% (Katipamula et al. 2003). Therefore, the impacts in Table 11 are overestimated by about 20%.

The energy cost impact for the six AHUs ranged from $500 to $5,000 for the six-month monitoring period. Although these results cannot be scaled directly to an annual basis because they are highly dependent on both indoor and outdoor conditions, the annual impacts will be significantly higher than the impacts reported in Table 11.

Table 11 – Summary of Problems and Cost Impact at 300 Capitol Mall for the Six Month Monitoring Period

AHU	Problem Detected	Problem Confirmed	Problem Corrected	Energy Cost Impact ($)
1	Outdoor-air damper problem – not economizing fully	Yes	No	5,000
2	Outdoor-air damper problem – not economizing fully; excess ventilation in heating mode; inadequate ventilation during morning start-up period	Yes	No	3,200
3	Outdoor-air damper problem – not economizing fully; excess ventilation in heating mode	Yes	No	650
4	Inadequate ventilation; not economizing fully	Yes	No	500
5	Excess ventilation in heating mode; and not fully economizing in cooling mode	Yes	No	3,450
6	Excess ventilation in heating mode	Yes	No	3,200
			Total Site Cost Impact	**16,000**

Table 12 – Heating and Cooling System Efficiency and Energy Costs

	Heating	Cooling
Efficiency	80%	2.5 COP
Cost	6$/mmBtu	0.15$/kWh

The estimated energy savings from correcting all problems at 300 Capitol Mall is about $16,000 (for the six month monitoring period). As stated earlier, these savings are probably overstated somewhat because the supply fan operation was assumed constant. On the other hand, other operation problems may be present in the AHUs, but the presence of the problem found may mask these other problems. Because the logic implemented in the OAE is *single-fault in* nature, the OAE only identifies one prominent fault at a time. As a result, addition opportunities to improve the performance of AHUs may be available, as well as the associated savings. The OAE will reveal other problems if applied again after the problem first identified here is corrected.

9 User Impressions of the WBD

An exit interview was conducted with Mr. Maron, the WBD site administrator for 300 Capitol Mall, in April 2003. The results of that interview and his general comments are presented and summarized in this section.

9.1 General

Comments from Mr. Maron were mixed, he thought the WBD diagnostic tool set helped him in evaluating trends and identifying operational issues related to the six AHUs at 300 Capitol Mall. In addition, he found the WBD diagnostics to be quite comprehensive which would provide building managers, operators, and owners with the ability to evaluate real-time data and perform corrective measures as required. Although corrective measures for the identified operational issues at the site were not preformed, his comments reflect only the diagnostics of the WBD OAE. However, he also commented that the modified data collection process was not fully automated. In addition, he thought the modular nature of the software was confusing from an operator's perspective.

9.2 OAE Interface and Diagnostics

On a scale of 1 to 5 (1 being very easy and 5 being very difficult to use) Mr. Maron gave the WBD a rating of 5 on ease of use. He indicated that the modular nature of the software made it difficult for an operator. He indicated that the OAE tool was only relevant for building operators and not the building managers or owners. He indicated that the configuration of the diagnostician was somewhat easy but required a lot of detailed information about the system.

Mr. Maron indicated that he reviewed results every six weeks and confirmed problems that the OAE reported by visually inspecting the AHUs. Despite this, none of the problems identified were corrected. When asked about recommendations for changes or improvements to the OAE/WBD, Mr. Maron indicated that the user interface needs to be simplified and he preferred the tool to be less modular.

10 Conclusions and Recommendations

The WBD OAE module was shown to successfully identify a number of major problems with the AHUs at 300 Capitol Mall. These findings are consistent with other demonstrations of the WBD, where the OAE found similar problems that should have been detected at the time of commissioning or periodic maintenance.

The OAE diagnostic module identified problems with all six AHUs at the demonstration site. Based on the results, we recommend a few corrective actions for the 300 Capitol Mall air handlers:

- Modify the damper controls on AHU-1 so that the damper is fully open during economizing operations; the current operations are improper and are costing the building

over $5,000 for the six month monitoring period

- Modify the damper controls on AHU-2 so that the damper is fully open during economizing operations and stop excess ventilation during heating mode operation. In addition, make sure that the AHU provides adequate ventilation during all times (including morning start-up); the current operations are improper and are costing the building **over $3,200** for the six month monitoring period

- Modify the damper controls on AHU-3 so that the damper is fully open during economizing operations and stop excess ventilation during heating mode operation; the current operations are improper and is costing the building **over $650** for the six month monitoring period

- Modify the damper controls on AHU-4 so that the damper is fully open during economizing operations and make sure it provides adequate ventilation at all times (including morning start-up); the current operations are improper and is costing the building **over $500** for the six month monitoring period

- Modify the damper controls on AHU-5 so that the damper is fully open during economizing operations and stop excess ventilation during heating mode operation; the current operations are improper and are costing the building **over $3,450** for the six month monitoring period

- Modify the damper controls on AHU-6 so that the AHU does not provide excess ventilation during heating mode operation; the current operations are improper and are costing the building **over $3,200** for the six month monitoring period.

Observations by users at the building provided mixed results. This may have implications for interface design changes in the future. For example, a simpler user interface that produces an action item list or list of problems based on OAE results for a block of time may be preferable to users overwhelmed by the detailed hourly results.

Installation of the WBD and collection of data from the air handlers were not smooth because of various reasons at this site. A modified automated process had to be developed after the start of the project, which cost us valuable demonstration time.

The demonstration reinforced the notion that diagnostic tools produce savings only when the identified problems are fixed. Merely identifying operation problems and their impacts is not sufficient by itself; building staff must fix them. If building staffs are not able to use their control systems to correct problems, are too busy with other duties, or lack resources to obtain help from contractors, savings will not be realized. A delivery mechanism is needed that helps ensure that building staffs take action when alerted to problems with significant impacts.

The time and cost of diagnostic-tool installation is a significant component to implementing diagnostic technologies. Labor costs to set up tools like the WBD (~1 week) will likely exceed the purchase cost of commercialized software. Sites with larger air handlers (10,000 cfm or larger air flow rates) have greater savings per problem fixed, while installation costs do not vary with air handler size (i.e., savings are greater relative to costs). Installation costs per air-handler also go down as the number of air handlers at a site increases, provided the units use similar operating control strategies and are part of the same underlying control system.

Overall, the WBD OAE diagnostician was successfully applied at 300 Capitol Mall. It identified problems with significant energy and cost penalties that would provide significant savings if fixed. Getting building staff to correct these problems, however, was difficult. This points to a need to develop a mechanism for delivering the OAE or providing its results to users in a way that better encourages them to correct the problems found.

The intent of this demonstration was to test the ability of the third-party service provider to use and interpret the results from the WBD tool. The service provider was supposed to have installed the tool at more than one building and review the results regularly from a central location. This would have provided a model by which HVAC service providers (like BayPoint Controls) to benefit from tools like the WBD/OAE. However, due to the limitation in automated data collections at the first site and lack of time and resources, limited the scope to a single building. Therefore, the service provider deployment model still needs to be developed and validated. Although the original objective was not totally met, the service provider (BayPoint Controls) was more proficient at the use of the tool, as we had expected, compared to the building operators at many of the earlier demonstrations.

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